Telescopes & Detectors

Workshop on Introduction to Astronomy and Astrophysics

IIT, Tirupati

24 January 2026

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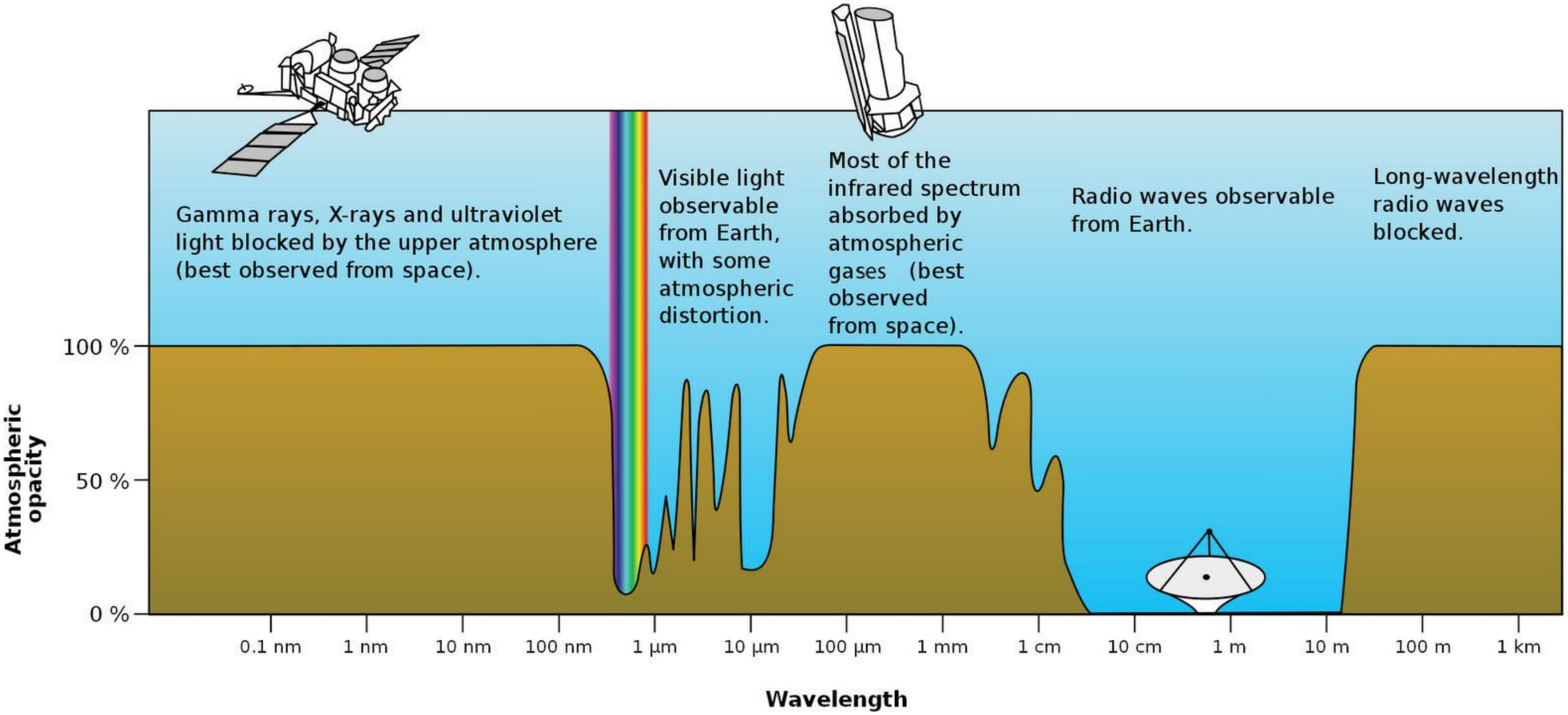
IUCAA

Reference Books

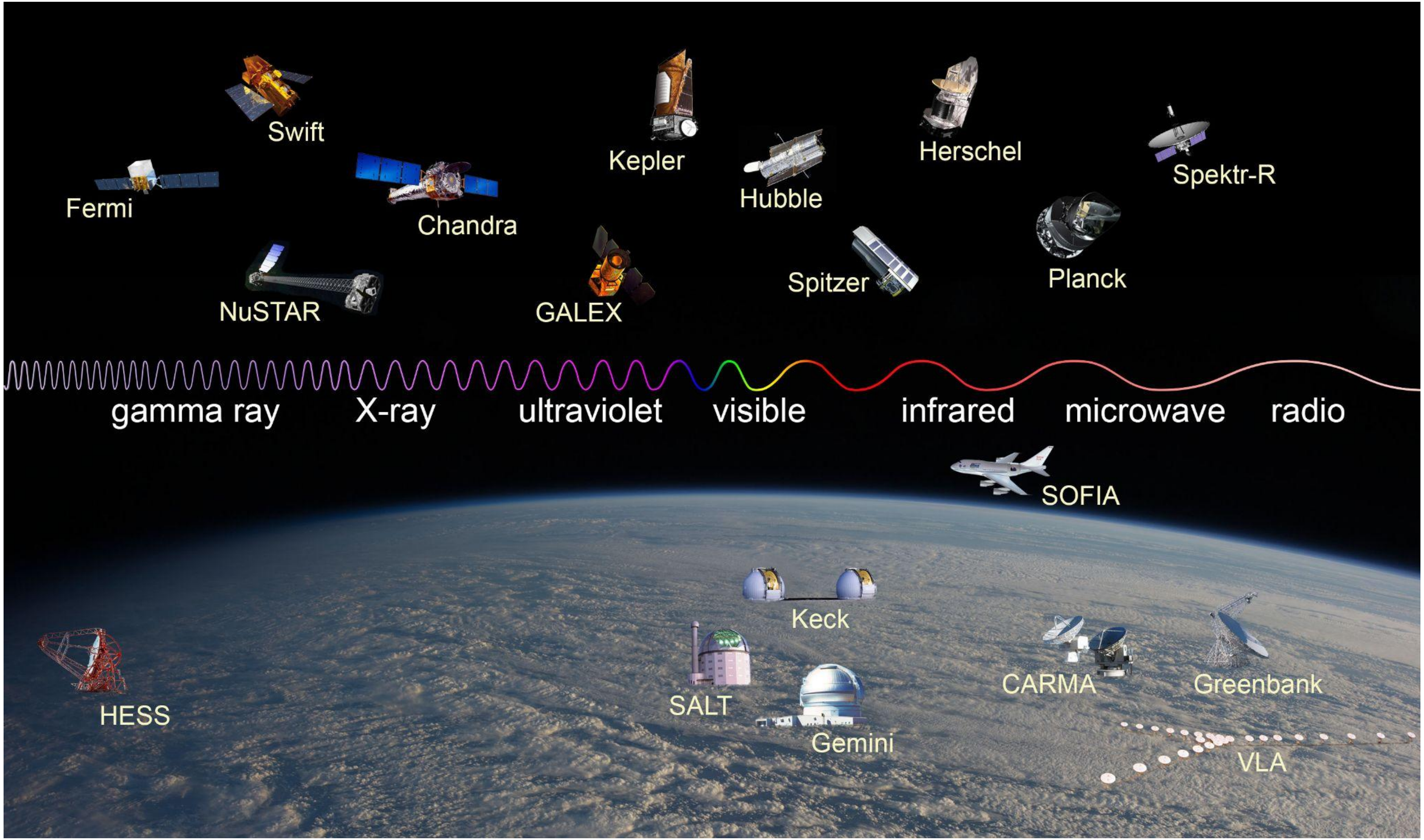
1) Astrophysical Techniques - *C. R. Kitchin*
2) Astronomical Optics - *Daniel J. Schroeder*
3) Observational Astronomy - *D. Scott Birney, Guillermo Gonzalez, David Oesper*
4) Optical, Infrared and Radio Astronomy: From Techniques to Observation - *Rosa Poggiani*
5) Physical Principles of Astronomical Instrumentation - *Peter A. R. Ade, Matthew J. Griffin, Carole E. Tucker*
6) Observational Astrophysics - *Pierre Lena, Daniel Rouan, Francois Lebrun, Francois Mignard, Didier Pelat*

Multiwavelength observations



NASA

Multiwavelength observations



NASA

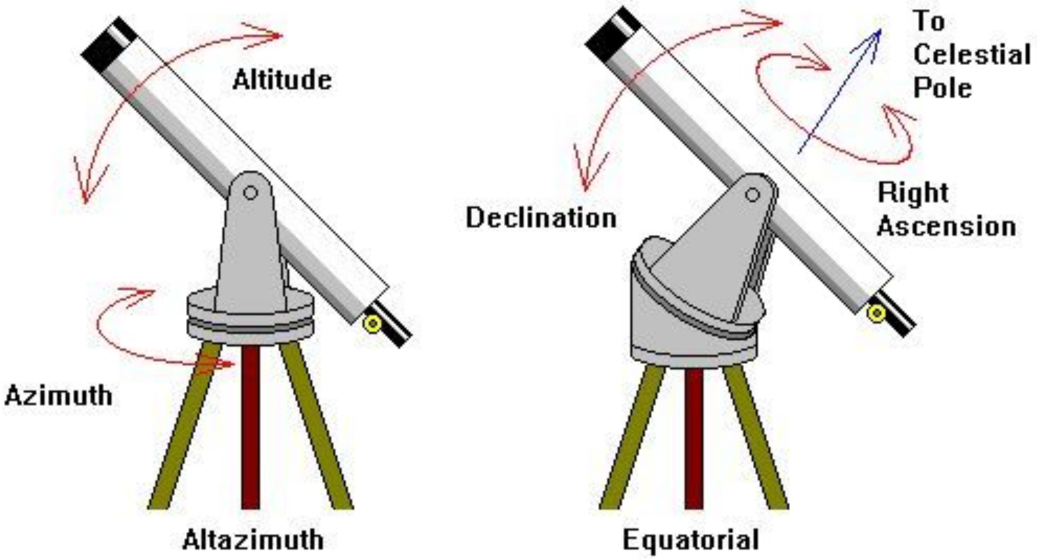
Telescope Mounts

Equatorial:

- One axis (polar axis) fixed parallel to the Earth's axis of rotation
- Pro: compensates for Earth’s rotation, tracks objects across sky
- Con: complicated, expensive

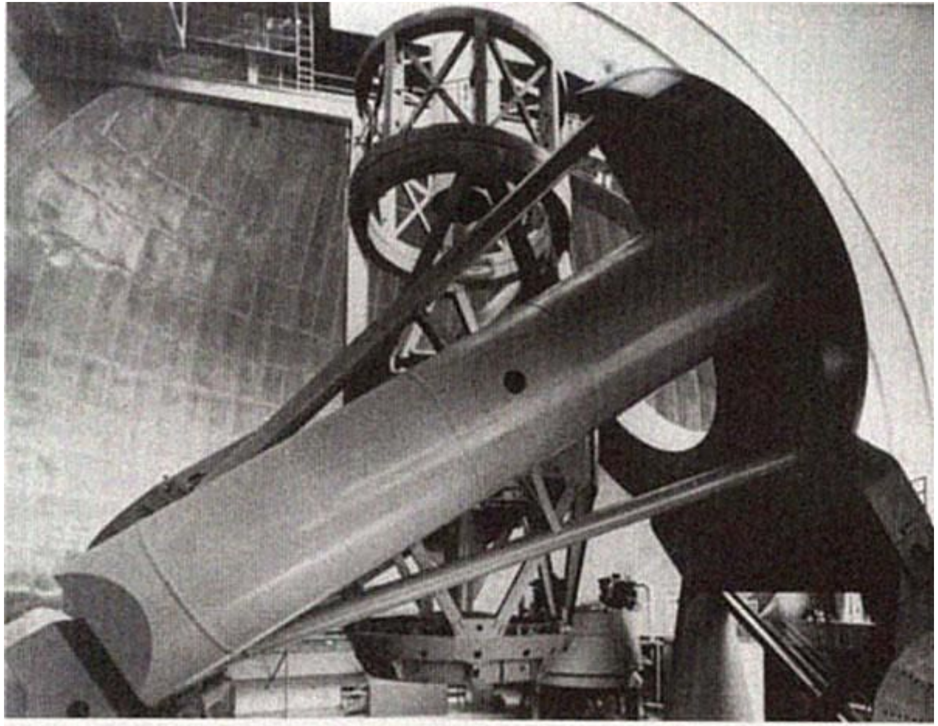
Alt-Azimuth:

- Two axes of rotation: horizontal and vertical
- Pro: simpler, cheaper
- Con: cannot track objects across sky, rotating field of view



Telescope Mounts

Large modern telescopes have Alt-Az mount



Mt. Palomar's 200-inch Hale Telescope, pointing to the zenith, as seen from the east side.

Very Large Telescope in Chile

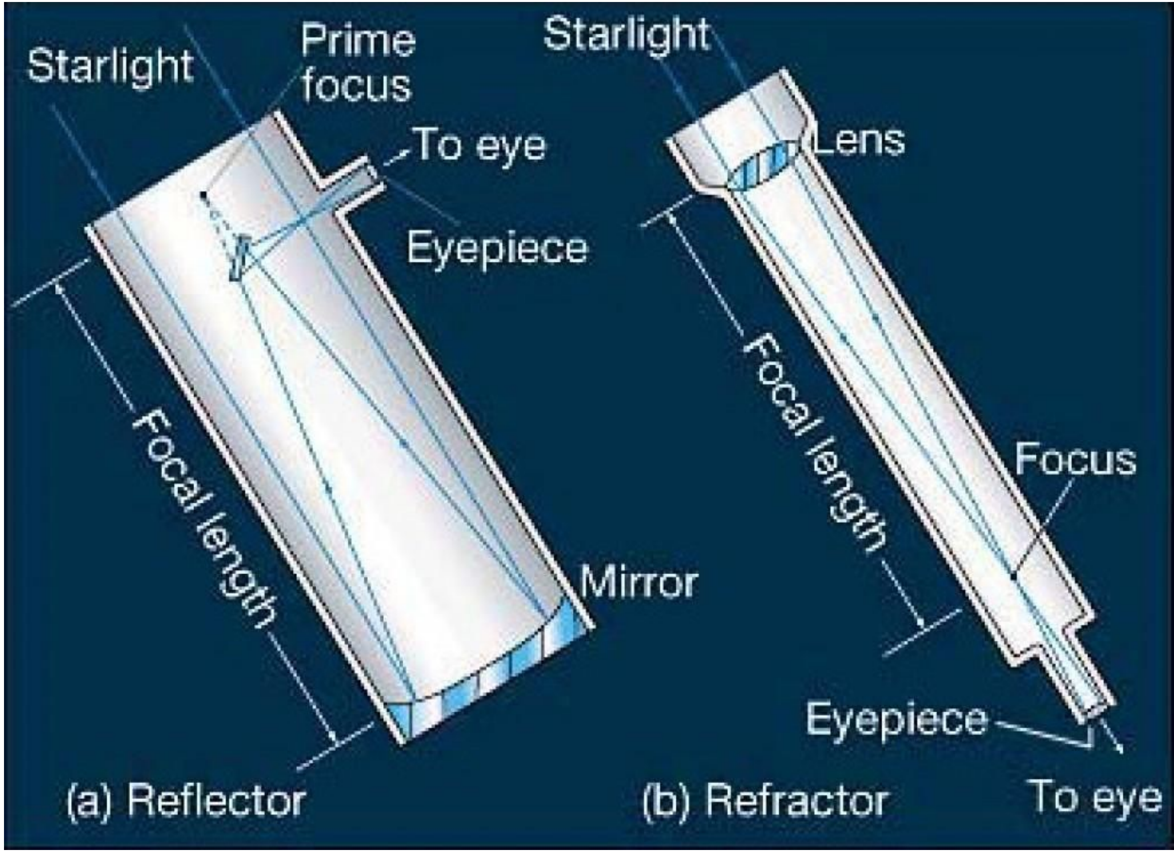
Telescope Types

Refractor

- Uses lenses
- Pros: Closed tube, sharper images
- Cons: Heavy, long tube, expensive, chromatic aberration

Reflector

- Uses mirrors
- Pros: Larger size, can be supported at back, cheaper
- Cons: Central obstruction, spherical aberration

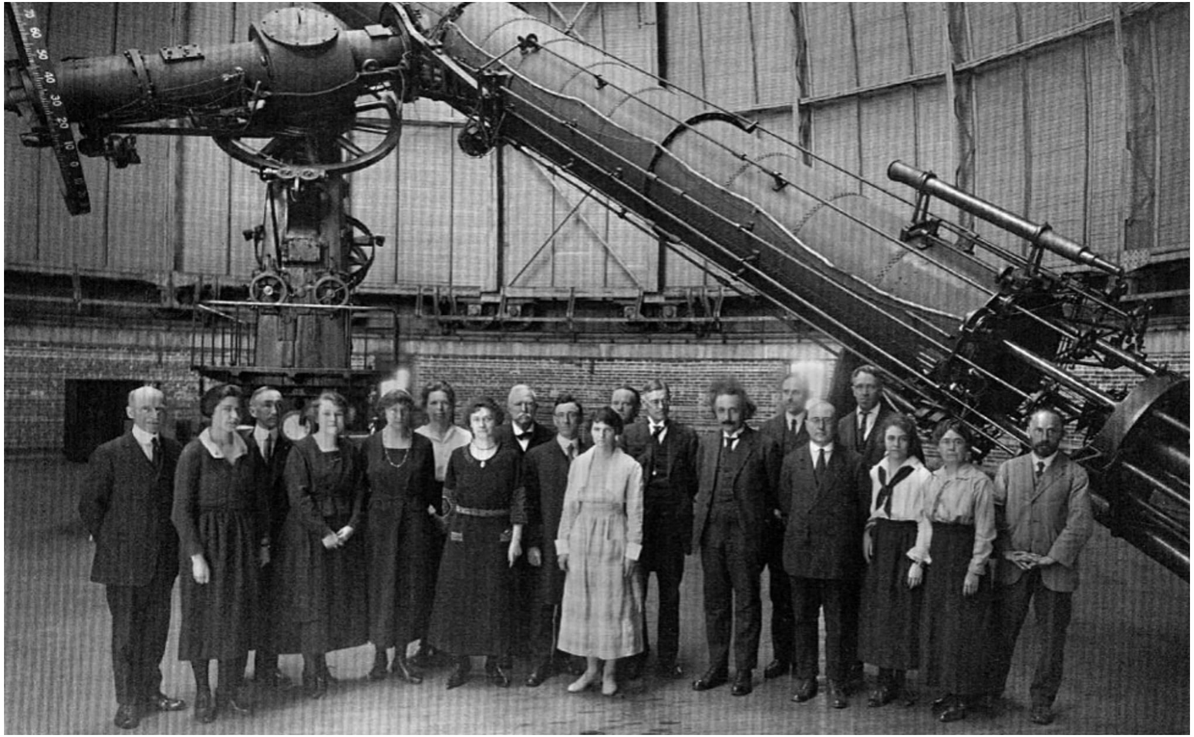


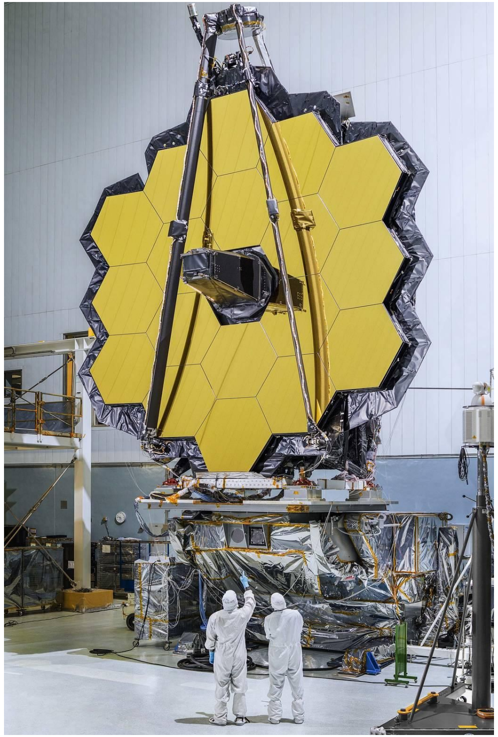
Hubble WFPC1 image of M101 before correction

Hubble WFPC2 image of M101 after correction

Telescope Types

Large modern telescopes are reflectors



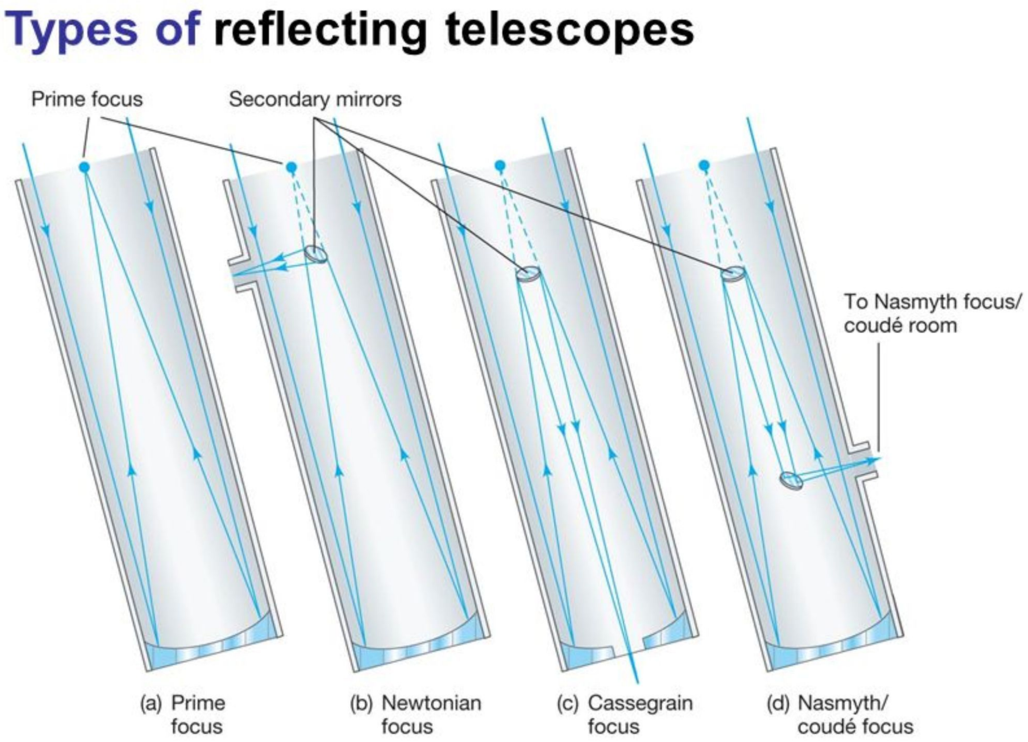


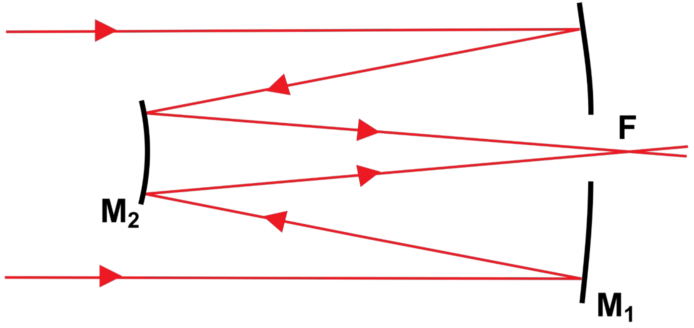
40 in refractor at Yerkes Observatory

JWST 6.5 m mirror

Telescope Design

Most common reflector type is Ritchey-Chrétien (variant of Cassegrain) with hyperbolic primary and hyperbolic secondary mirrors





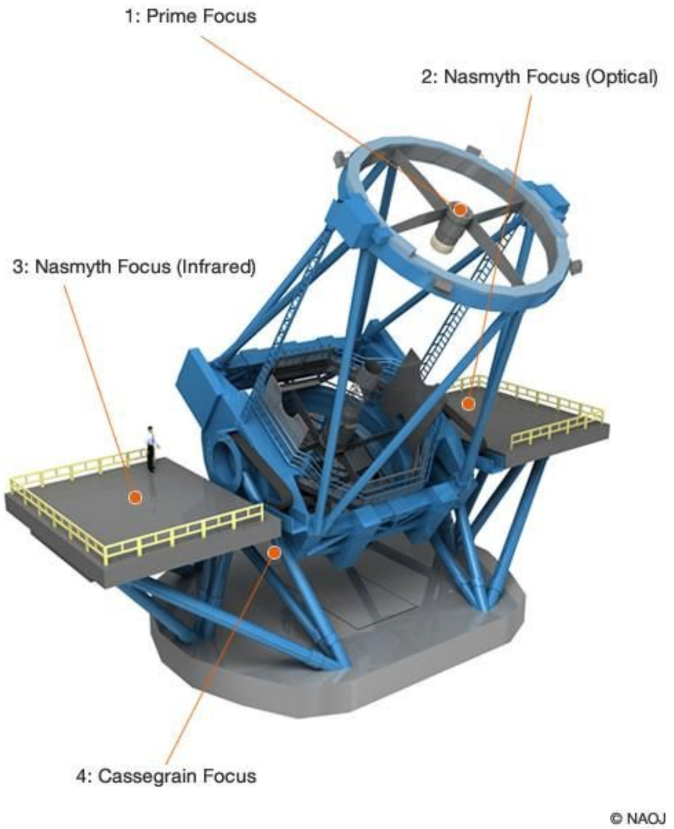
Ritchey-Chrétien

Examples: Hubble Space Telescope, Keck Telescope, Very Large Telescope

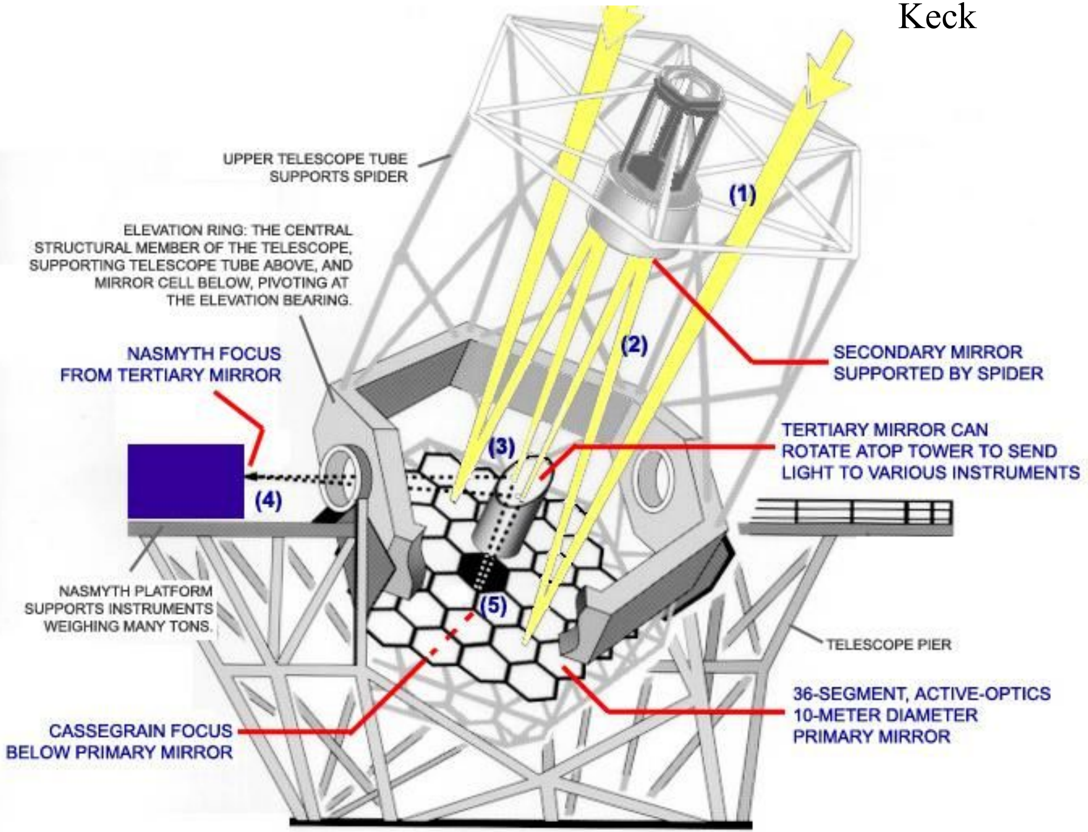
Telescope Design

Large instruments are usually hosted at Nasmyth focii

Subaru

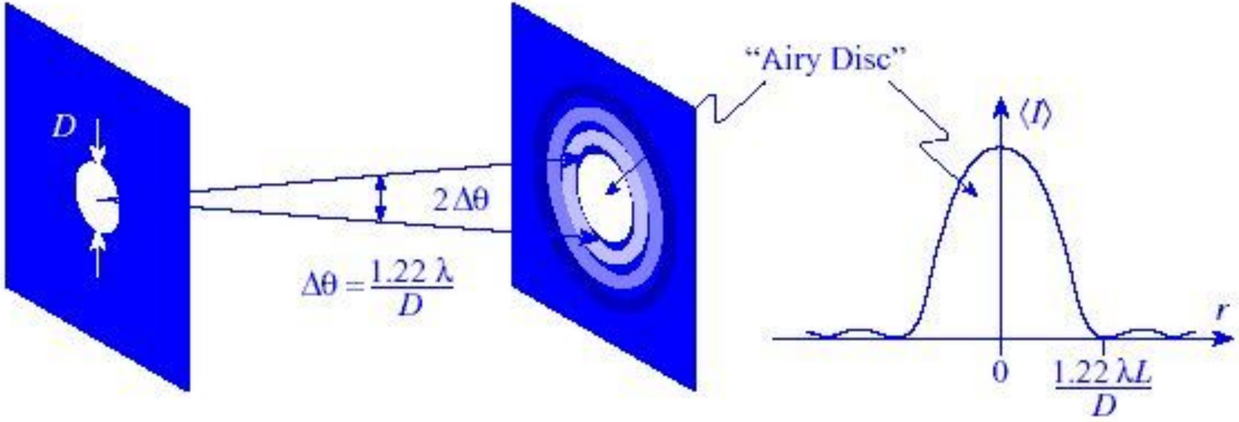


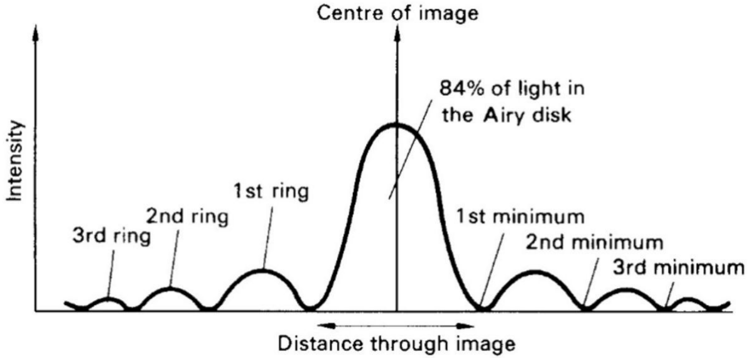
Keck



Airy Profile

Diffraction pattern resulting from a uniformly illuminated, circular aperture (primary mirror of telescope)





First minimum occurs at

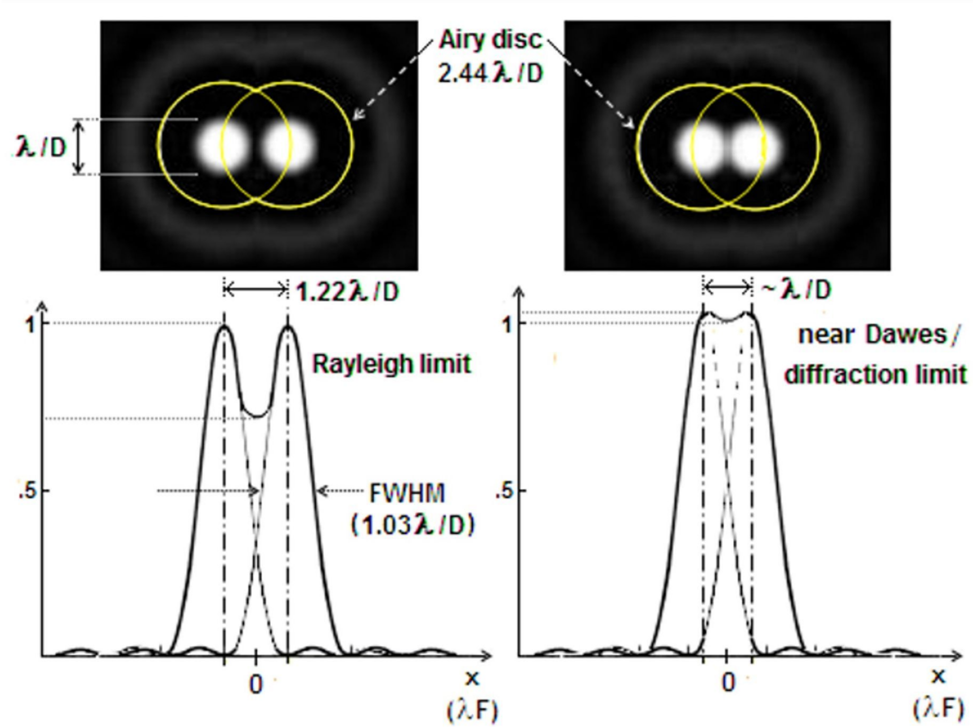
$$\sin\theta \approx 1.22\frac{\lambda}{d}$$

or, for small angles, simply

$$\theta \approx 1.22\frac{\lambda}{d},$$

Angular Resolution

Rayleigh Criterion: two point sources are said to be just resolved when the principal diffraction maximum (center) of the Airy disk of one image coincides with the first minimum of the Airy disk of the other



Diffraction limit of telescope:

$$\theta \approx 1.22\frac{\lambda}{D} \quad (\text{considering that } \sin\theta \approx \theta)$$

Angular Resolution

Calculate diffraction limit for VLT (D=8.2 m) and HST (D=2.4 m) in optical band (500 nm)

Angular Resolution

Calculate diffraction limit for VLT (D=8.2 m) and HST (D=2.4 m) in optical band (500 nm)

1 radian ~ 206265”

VLT ~0.01”, HST~0.04”

Angular Resolution

Calculate diffraction limit for VLT (D=8.2 m) and HST (D=2.4 m) in optical band (500 nm)

1 radian ~ 206265”

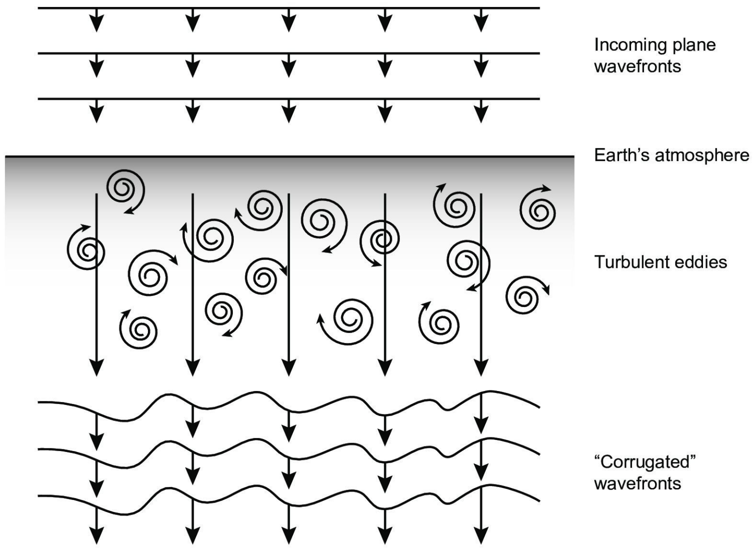
VLT ~0.01”, HST~0.04”

In practice, FWHM of point sources (stars) in VLT images (point spread function or PSF) much larger than diffraction limit…Why?

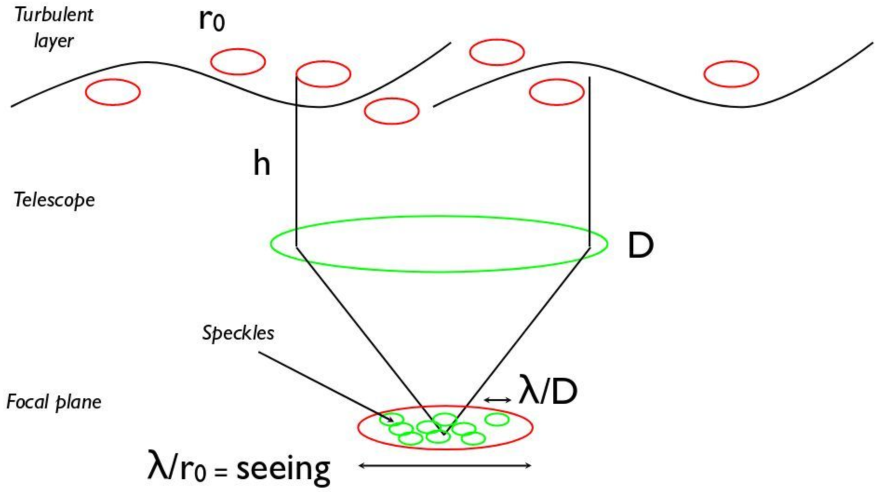
Effects of Earth's Atmosphere

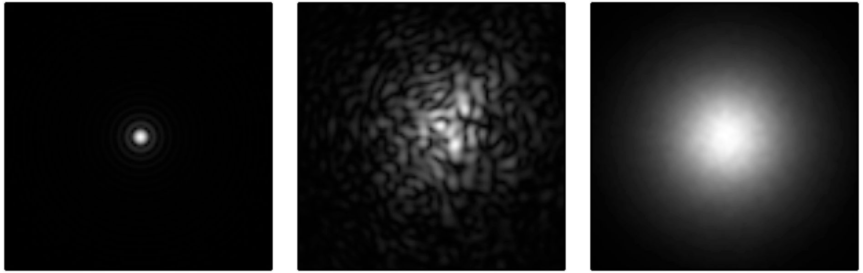
1. Refraction
2. Night sky emission (moonlight, thermal emission, air glow, light pollution, zodiacal light)
3. Extinction - absorption (e.g. by molecules) + scattering (e.g. Rayleigh scattering)
4. Turbulence - scintillation (change in brightness) + seeing (change in position)

Seeing



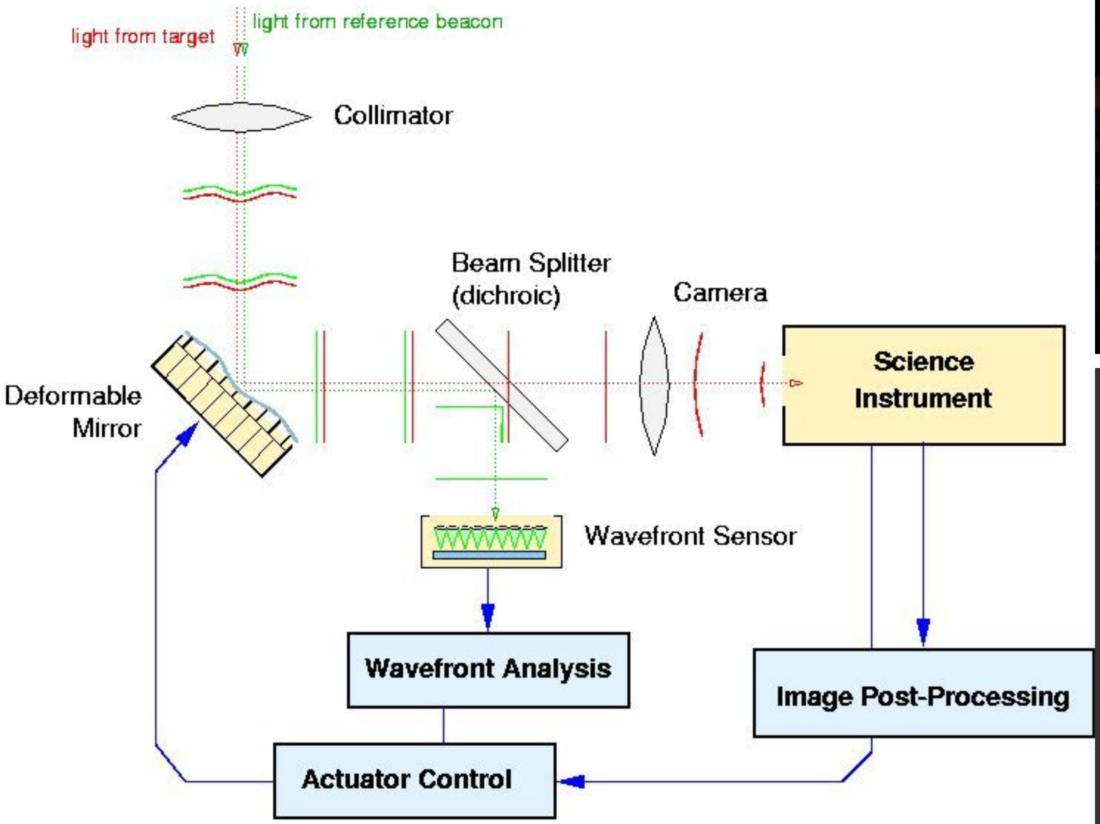
Speckles and seeing halo

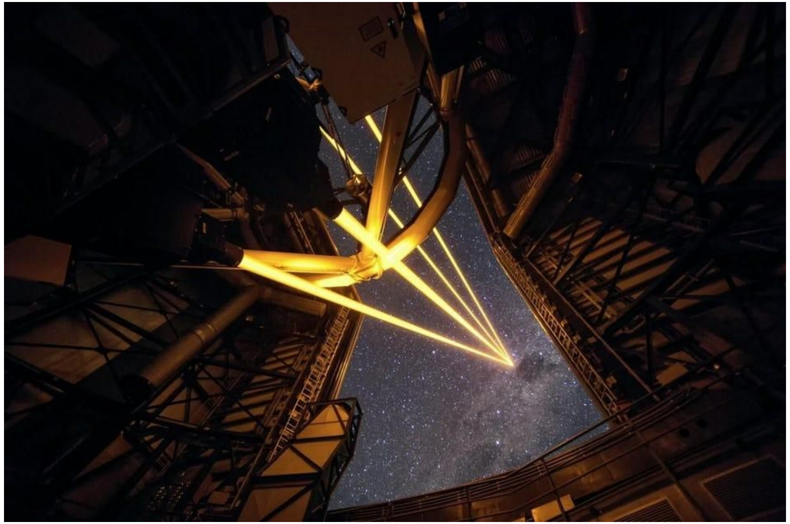


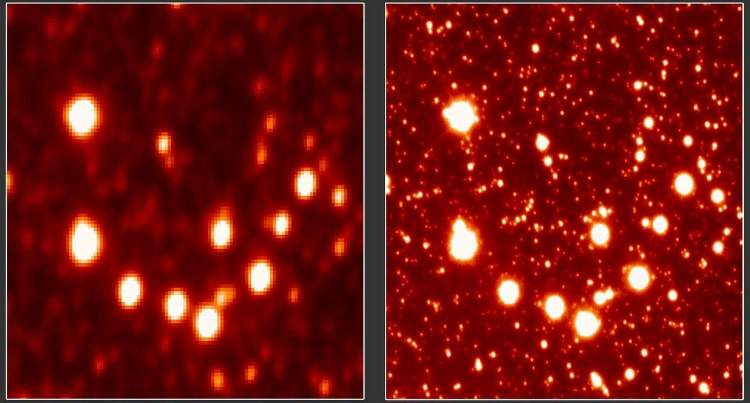


Fried's parameter or coherence length (r0) is defined as the diameter of a circular area over which the rms wavefront error due to passage through the atmosphere is equal to 1 radian. Telescopes with apertures D larger than r0 will be seeing limited. Larger the r0, better the seeing. Best observing conditions (e.g. Paranal, Chile) have r0 ~20 cm or seeing ~0.6" in optical.

Adaptive Optics







Without Adaptive Optics

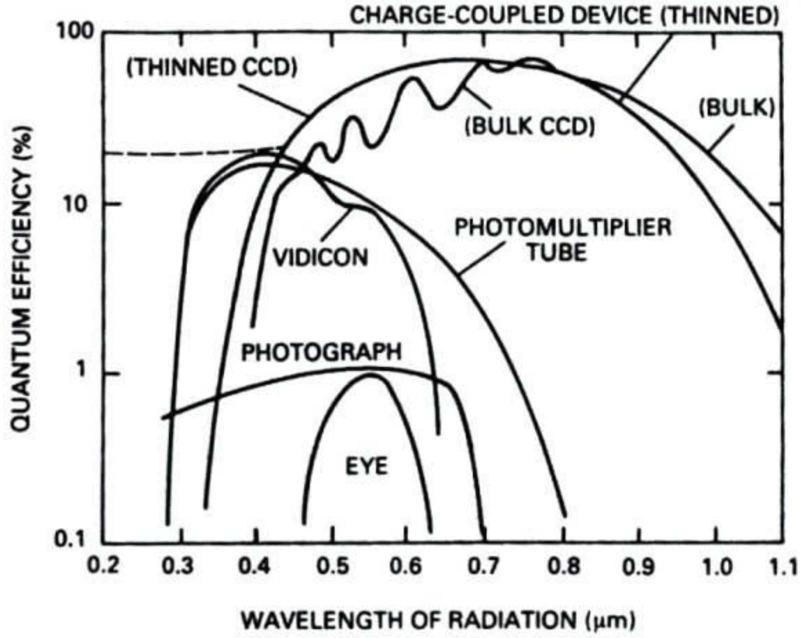
With Adaptive Optics with MAD

Detectors

Properties of an ideal telescope detector:

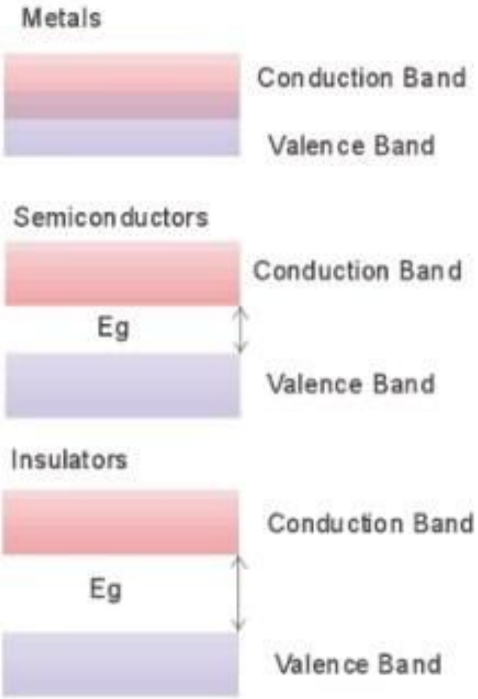
- Counts every photon it receives
- Large dynamic range
- Linear response
- Low noise
- Stable

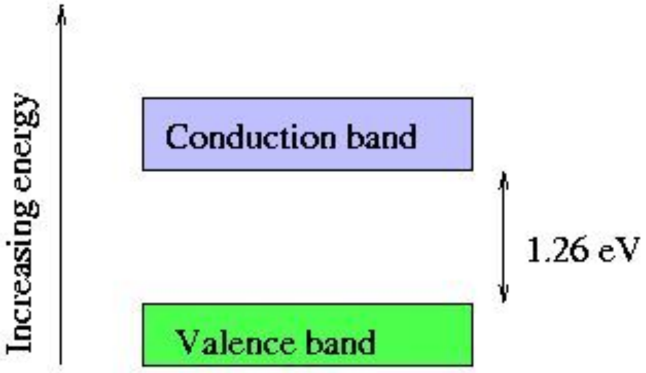
QE = Detected photons / Incoming photons

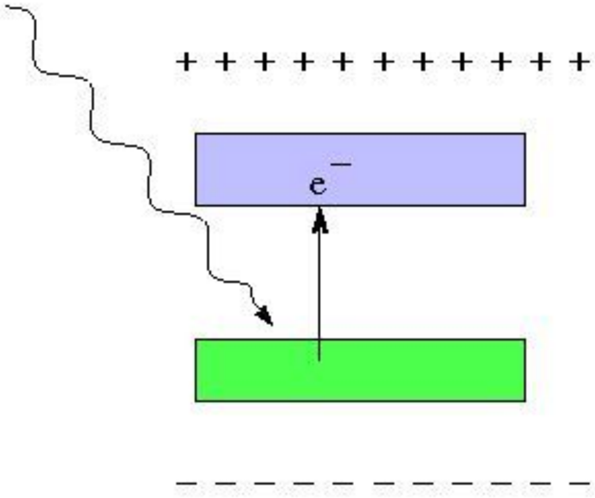


Charged Coupled Device (CCD)

Basic principle: Photoelectric effect in semiconductors







Charged Coupled Device (CCD)

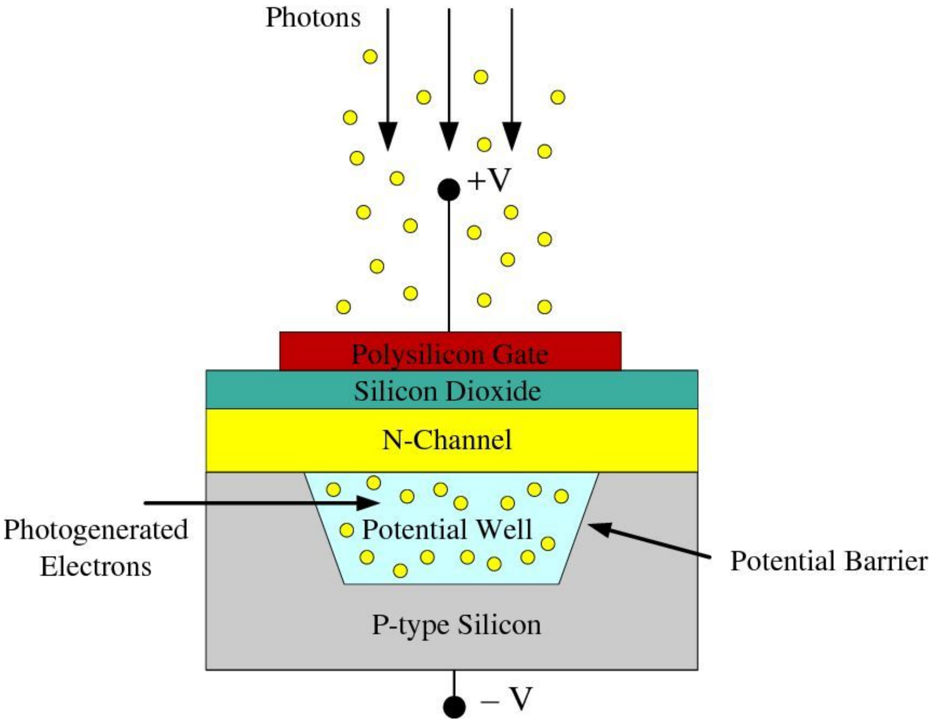
Only photons above a minimum energy (or below cut-off wavelength) will be absorbed and detected

$$\lambda_{co} = \frac{hc}{E_g} = \frac{1240\ nm}{E_g(eV)}$$

Material	Bandgap	λ_{max}
Silicon	1.1 eV	11,000 Å (1.1μ)
Germanium	0.67 eV	18,000 Å (1.8μ)
InSb	0.18 eV	6.7μ

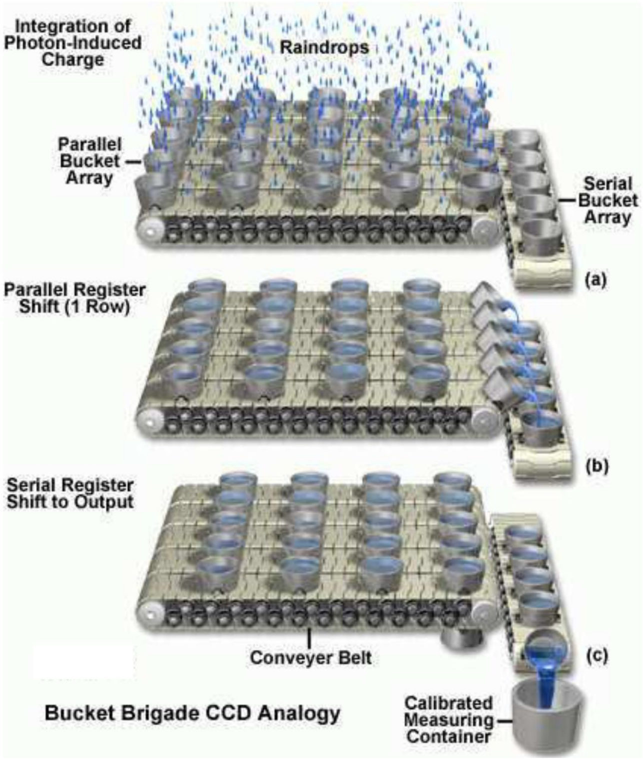
Charged Coupled Device (CCD)

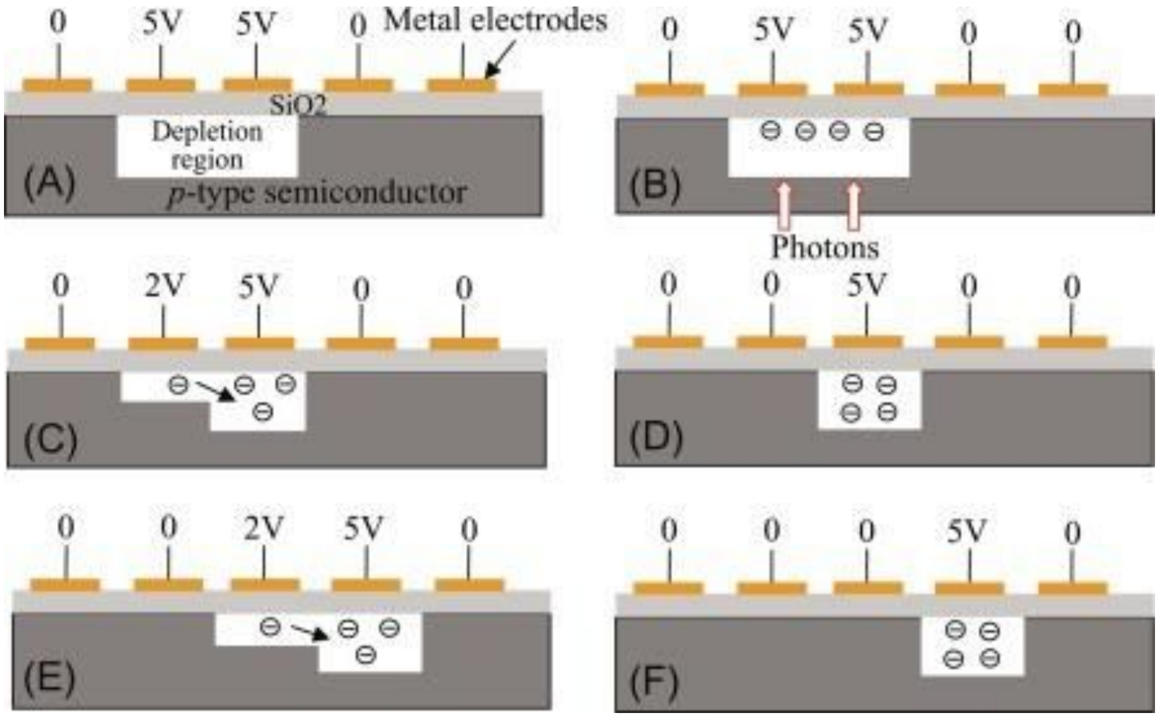
Every pixel in a CCD is a p-n junction diode reverse biased



Charged Coupled Device (CCD)

Principle of operation: Charge Transfer (Conveyor Belt Analogy)





Charge transfer efficiency CTE ~ 99.999 %

Noise Sources

1. Shot noise (Poisson noise)

    i. Object

    ii. Sky

    iii. Thermal noise of CCD

2. Read-out noise of CCD

Noise Sources

1. Shot noise (Poisson noise)

   i. Object $\sim \sqrt{N_{obj}} \sim \sqrt{(S_{obj} * t_{exp})}$

   ii. Sky $\sim \sqrt{N_{sky}} \sim \sqrt{(S_{sky} * t_{exp} * n_{pix})}$

   iii. Thermal noise of CCD $\sim \sqrt{N_{dark}} \sim \sqrt{(S_{dark} * t_{exp} * n_{pix})}$

2. Read-out noise of CCD $\sim R * \sqrt{n_{pix}}$

$$\text{Total Noise N } (e^-) = \sqrt{(S_{obj} * t_{exp} + n_{pix} * (S_{sky} * t_{exp} + S_{dark} * t_{exp} + R^2))}$$

S_{obj} = e^-/s from object S_{sky} = e^-/s/pixel from sky background
S_{dark} = e^-/s/pixel due to thermal noise in CCD (Dark current)
t_{exp} = exposure time in s n_{pix} = no. of pixels covered by object *R* = read noise per pixel in e^-

CCD S/N Equation

$$S/N = (S_{obj} * t_{exp}) / \sqrt{(S_{obj} * t_{exp} + n_{pix} * (S_{sky} * t_{exp} + S_{dark} * t_{exp} + R^2))}$$

Limiting Cases:

1. Object limited

$$S/N = (S_{obj} * t_{exp}) / \sqrt{(S_{obj} * t_{exp})} = \sqrt{(S_{obj} * t_{exp})} \propto D * \sqrt{t_{exp}}$$

($S_{obj} \propto D^2$; D = diameter of telescope mirror)

2. Background / Sky limited

$$S/N = (S_{obj} * t_{exp}) / \sqrt{(n_{pix} * S_{sky} * t_{exp})} \propto D * \sqrt{t_{exp}} \quad (S_{obj} \propto D^2 \text{ and } S_{sky} \propto D^2)$$

3. Read-noise limited

$$S/N = (S_{obj} * t_{exp}) / (R * \sqrt{n_{pix}}) \propto D^2 * t_{exp}$$

CCD S/N Equation

General version:

$$S/N = (S_{obj} * t_{exp} * G) / \sqrt{(S_{obj} * t_{exp} * G + n_{pix} * (1 + n_{pix}/n_{sky})*(S_{sky} * t_{exp} * G + S_{dark} * t_{exp} + R^2 + G^2\sigma_f^{\,2}))}$$

ADU = Analog to Digital Unit

S_{obj} = ADU/s from object

S_{sky} = ADU/s/pixel from sky background

S_{dark} = e^-/s/pixel due to thermal noise in CCD (Dark current)

t_{exp} = exposure time in s

n_{pix} = no. of pixels covered by object

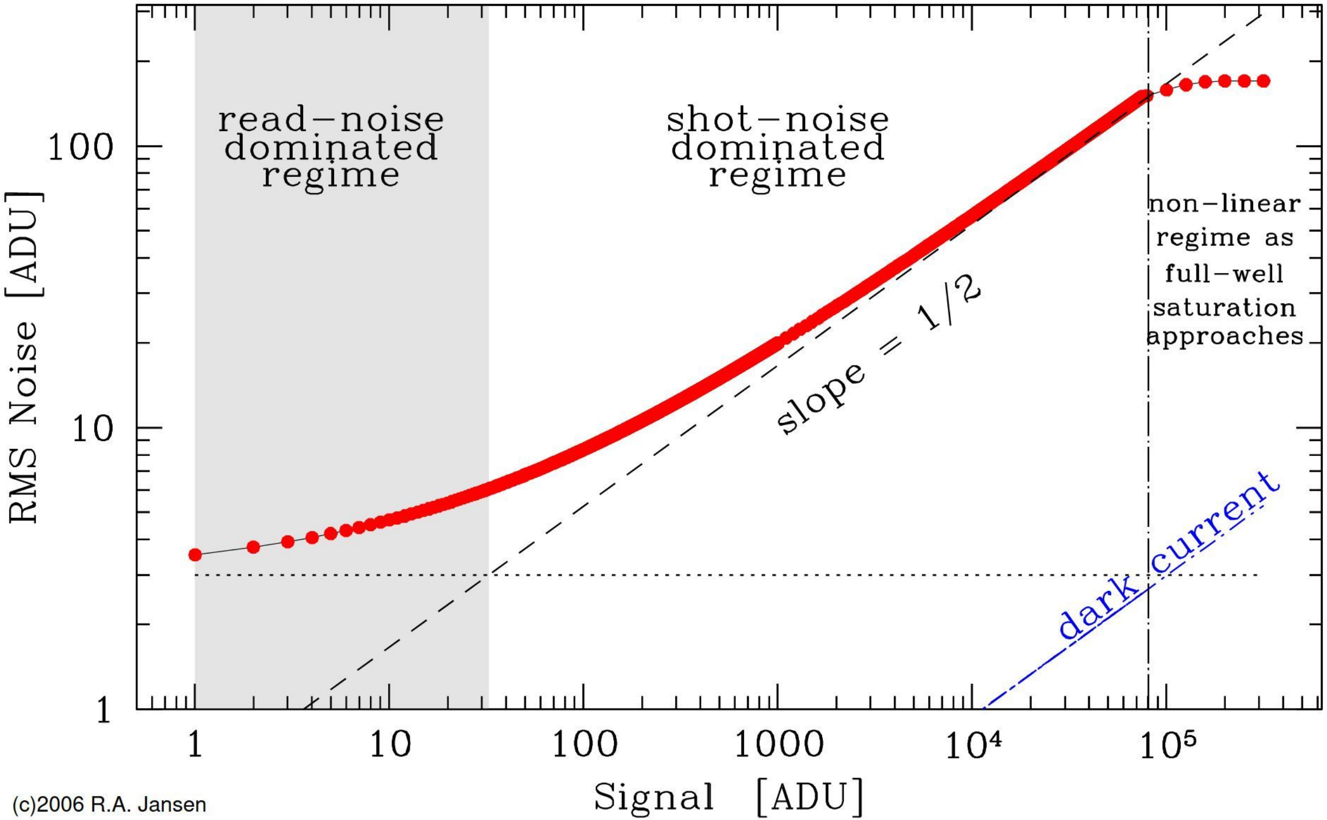
n_{sky} = no. of sky background pixels

R = read noise per pixel in e^-

G = CCD gain in e^-/ADU

σ_f = A to D conversion or digitization noise

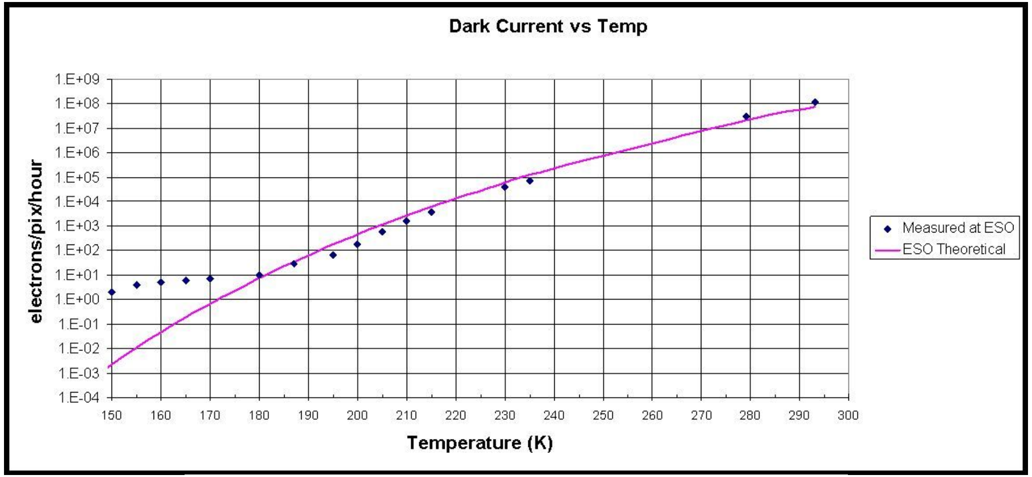
CCD Noise



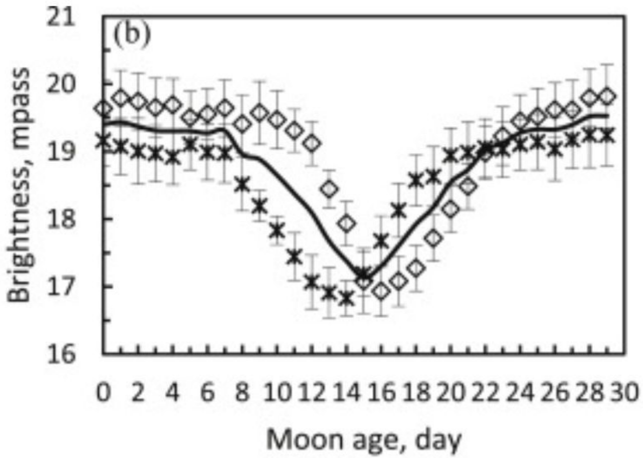
read−noise dominated regime
shot−noise dominated regime
non−linear regime as full−well saturation approaches
slope = 1/2
dark current
RMS Noise [ADU]
Signal [ADU]
1
10
100
1000
10^4
10^5
(c)2006 R.A. Jansen

Typical Noise

- Dark current: temperature dependent
  < 10 e^-/pix/hr for T ~ 150–170 K
- Read-noise: ~3–10 e^-/pix
- Gain: ~ 1 e^-/ADU
- A/D noise: $\sigma_f \sim 0.289$
- Sky brightness: depends on moon, location, wavelength

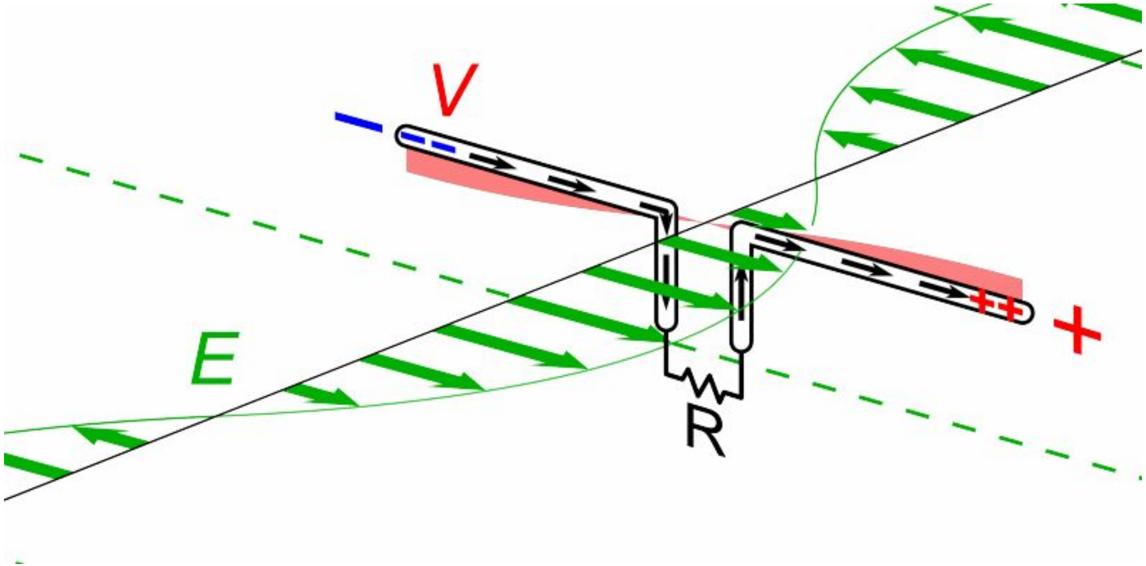


Sky Brightness (mag/arcsec2)					
lunar age (days)	U	B	V	R	I
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

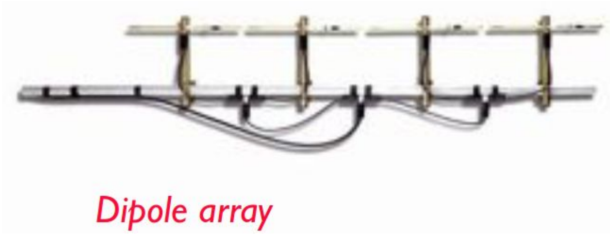


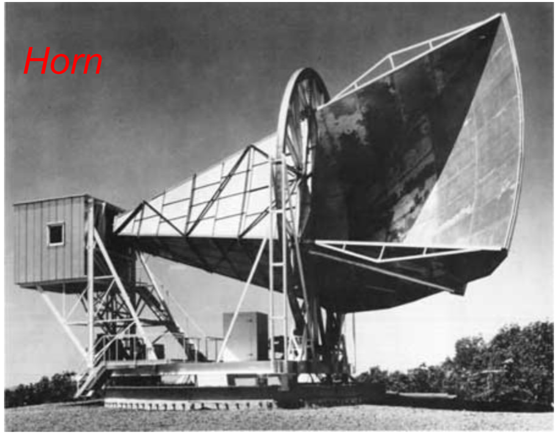
What do radio telescopes measure?

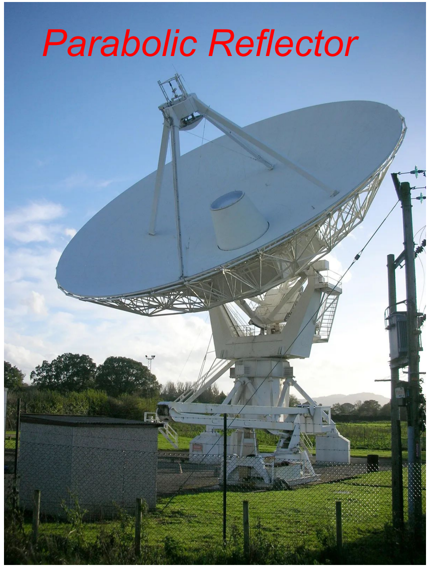
- Radio photons are too weak, cannot usually detect individual radio photons
- Instead measure the wave nature of EM radiation
- Antenna converts EM radiation into electrical currents in wires (receiving) or vice versa (transmitting)

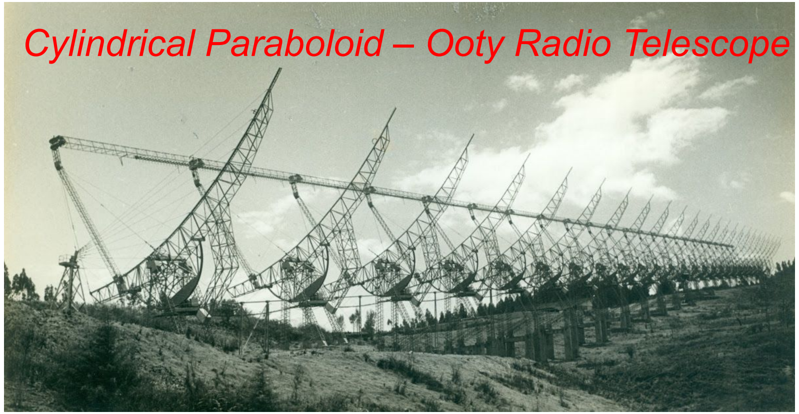


Radio Antennas









Single Dish

Prime Focus
e.g. GMRT

Cassegrain Focus
e.g. Mopra (AT)

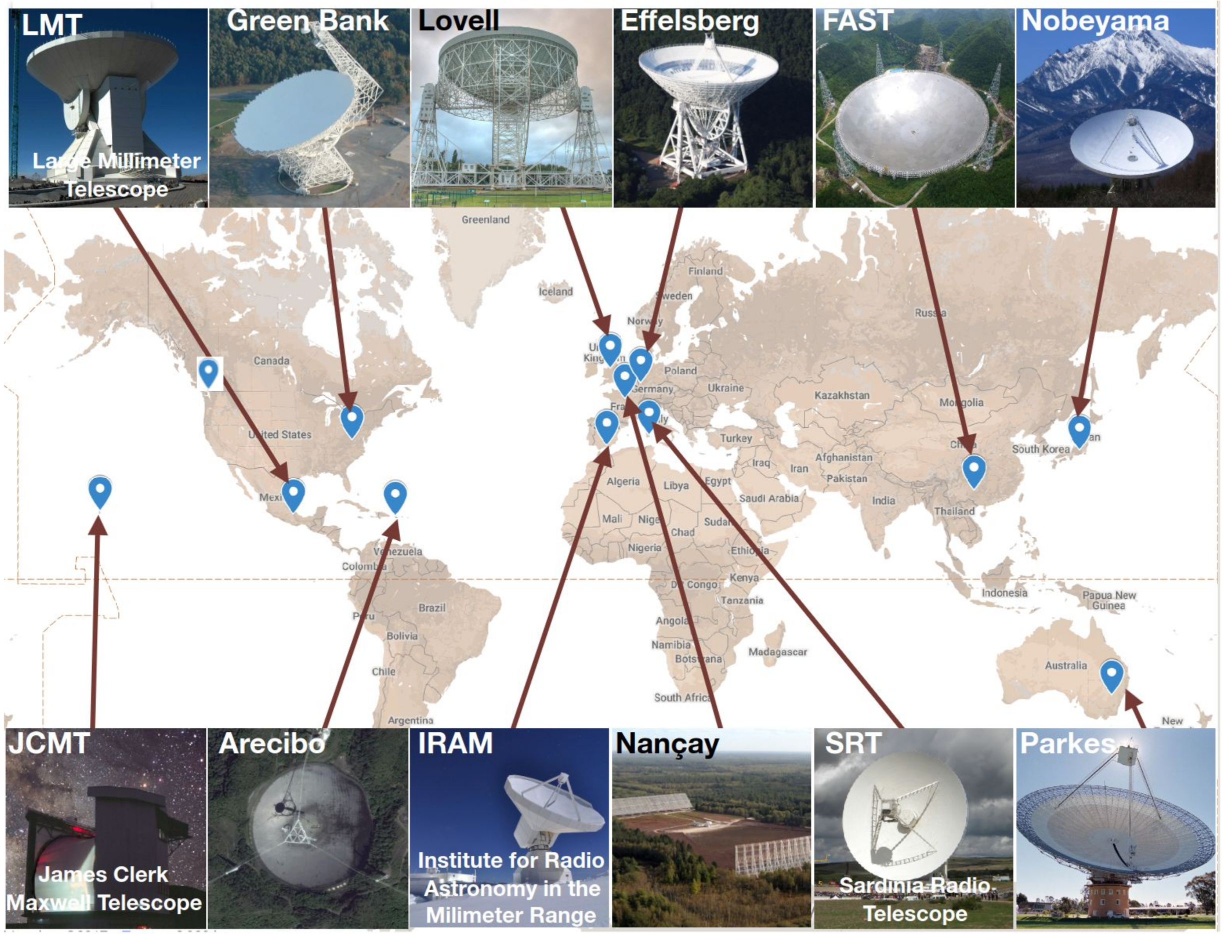
Offset Cassegrain
e.g. VLA and
ALMA

Naysmith
e.g. OVRO

Beam Waveguide
e.g. NRO

Dual gregorian
offset
e.g. ATA

Single Dish


LMT
Large Millimeter Telescope
Green Bank
Lovell
Effelsberg
FAST
Nobeyama
JCMT
James Clerk Maxwell Telescope
Arecibo
IRAM
Institute for Radio Astronomy in the Milimeter Range
Nançay
SRT
Sardinia Radio Telescope
Parkes

Need for Interferometry

Single Dishes

GBT

Parkes

Arecibo

Interferometers

GMRT

WSRT

LOFAR

SKA

SKA Mid

SKA Low

SKA Aperture Array

Angular Resolution

$\boldsymbol{\theta \sim \lambda / D}$

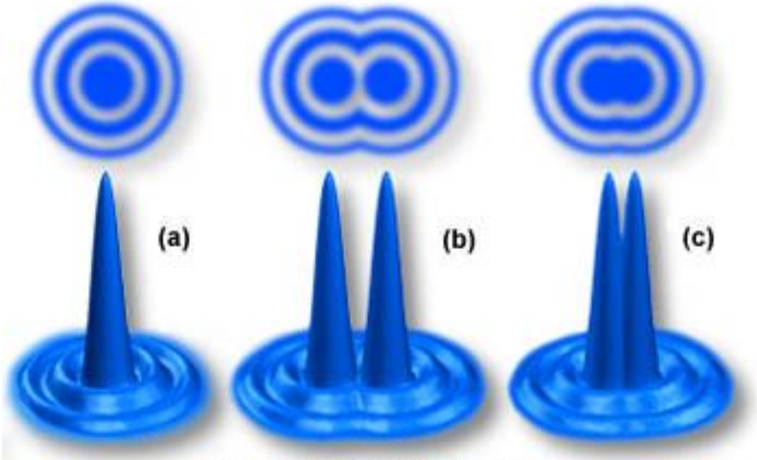
For single dish,

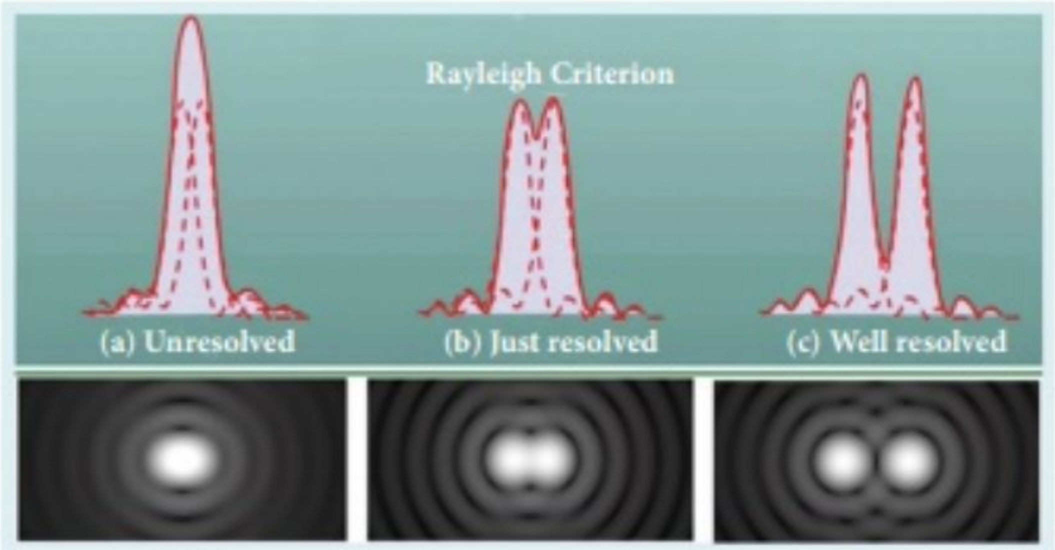
D: diameter of dish

For interferometers,

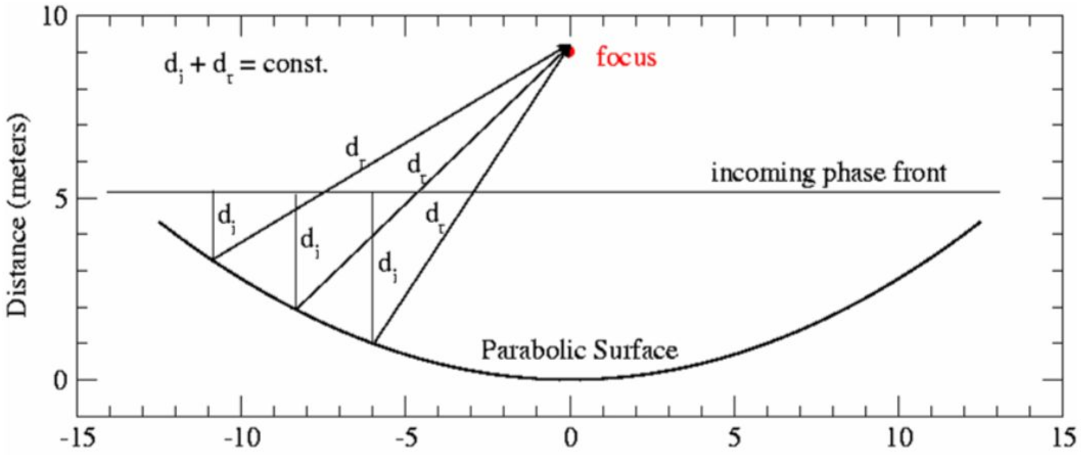
D: longest baseline or

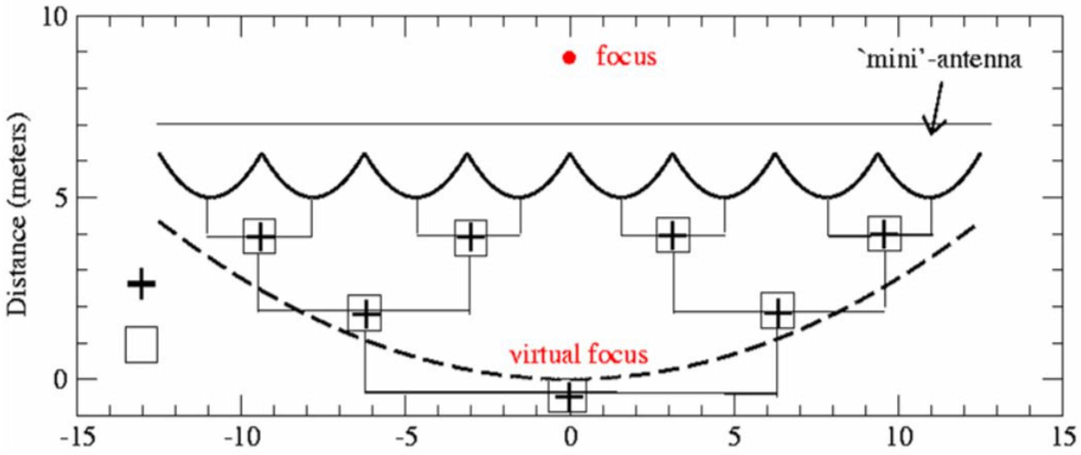
separation between telescopes





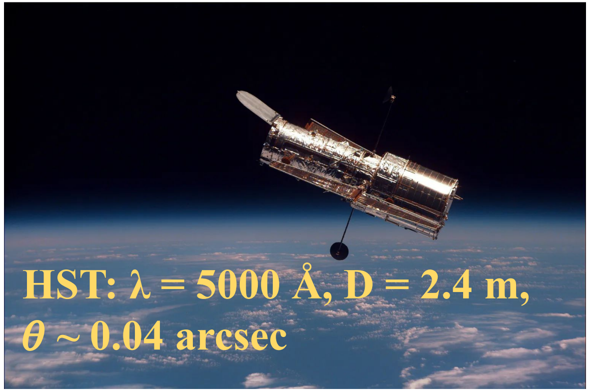
Basic Interferometry

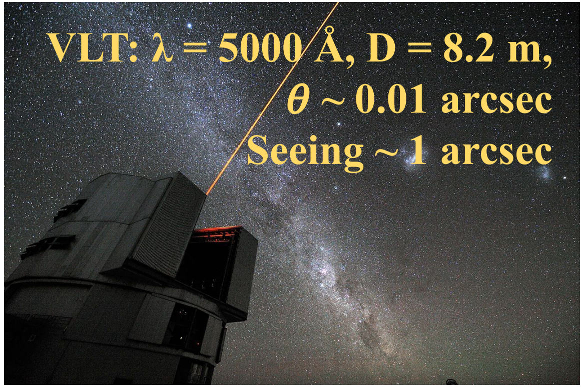


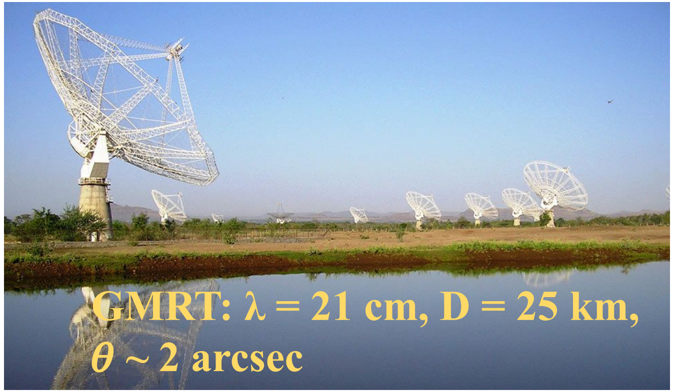


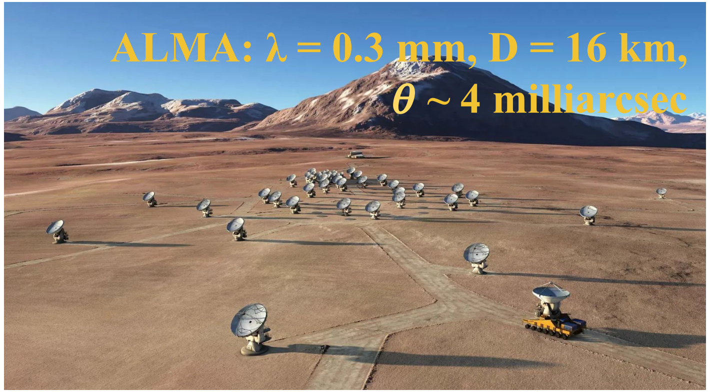
Radio Interferometry

Radio interferometry can achieve extremely high angular resolution ($\boldsymbol{\theta} \sim \lambda/\mathrm{D}$)



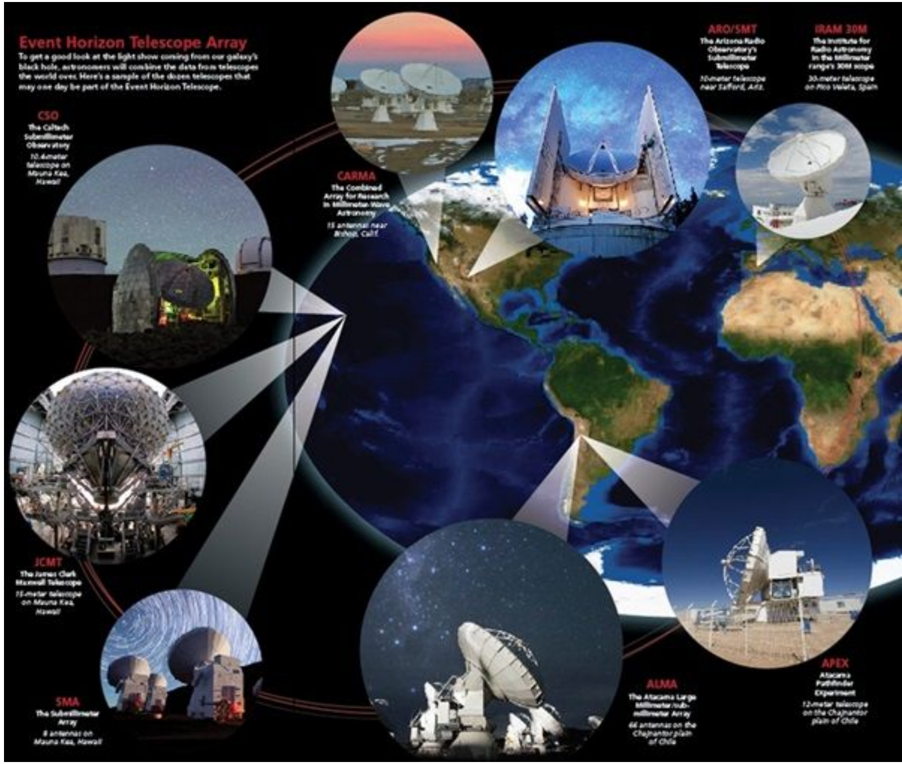




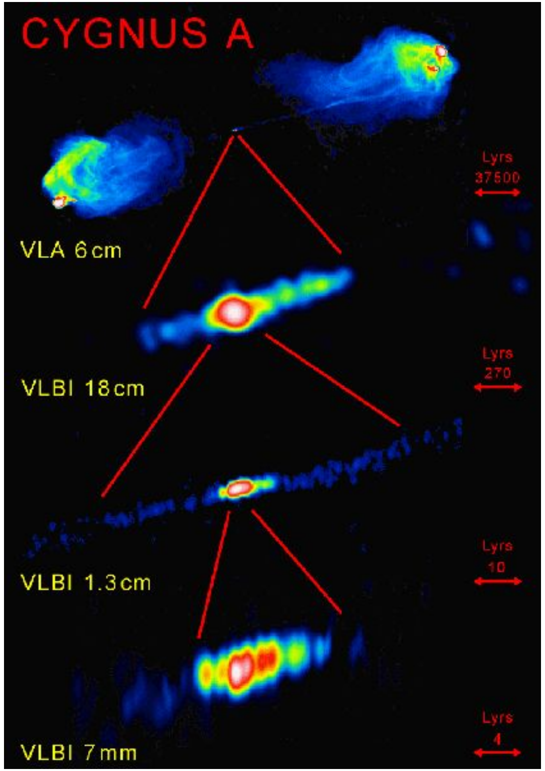


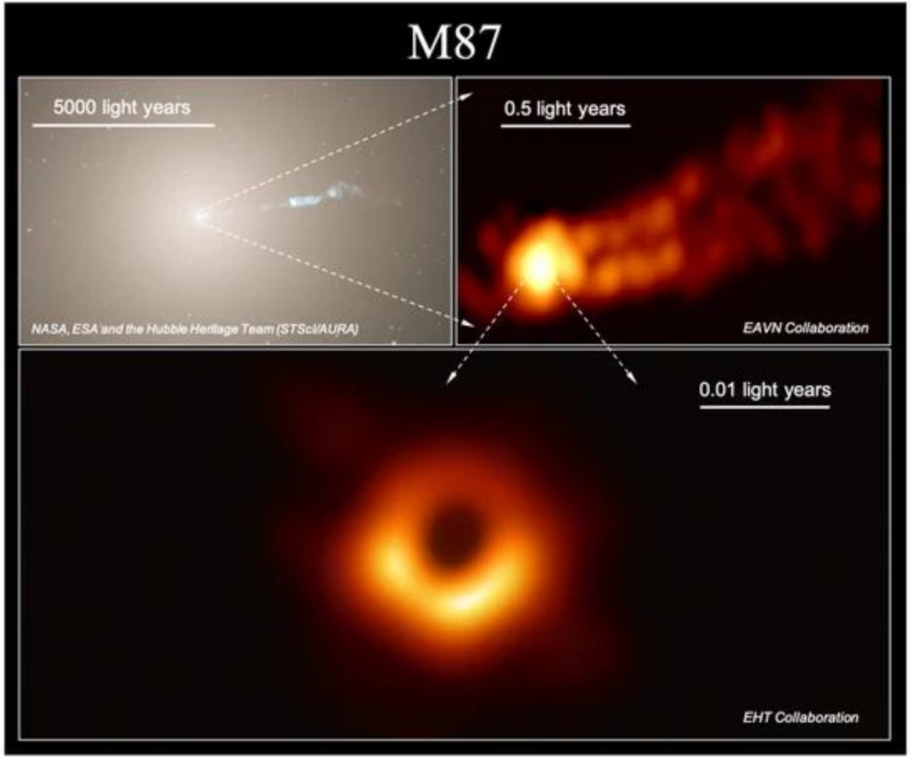
NASA
ESO
NCRA
NRAO

Very Long Baseline Interferometry (VLBI)



Science with Interferometry





MPIfR, EHT