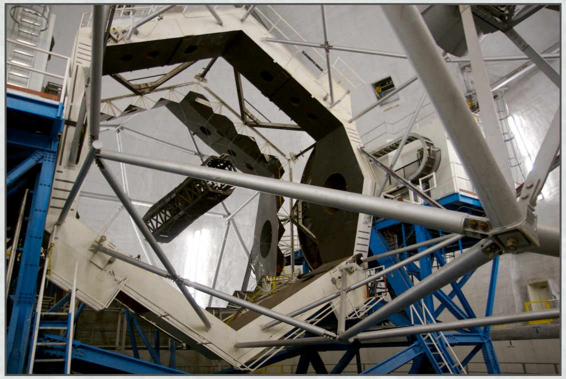
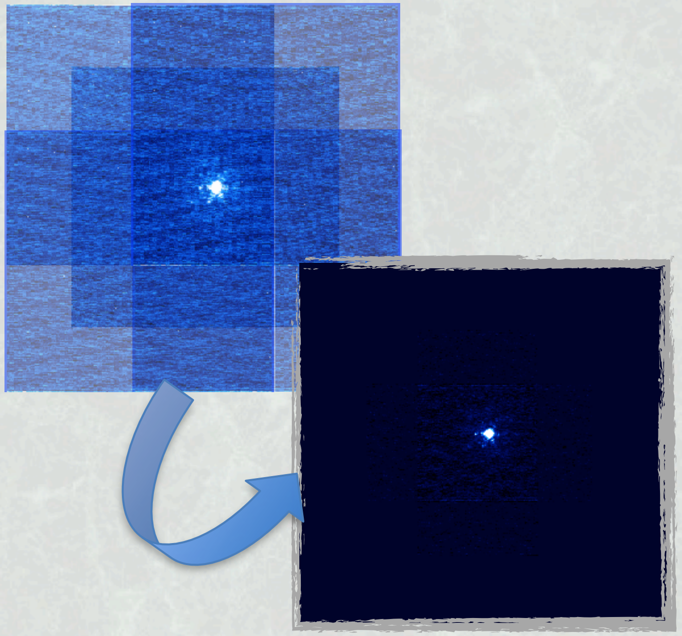
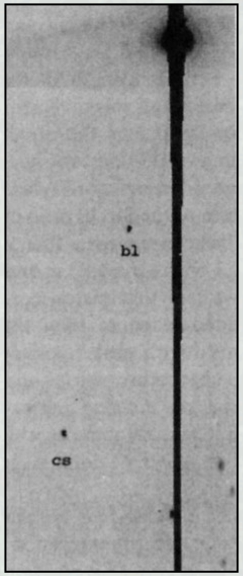
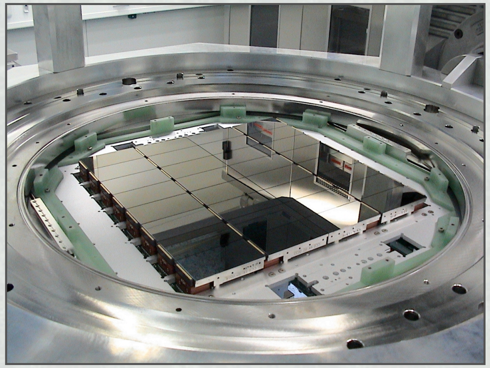
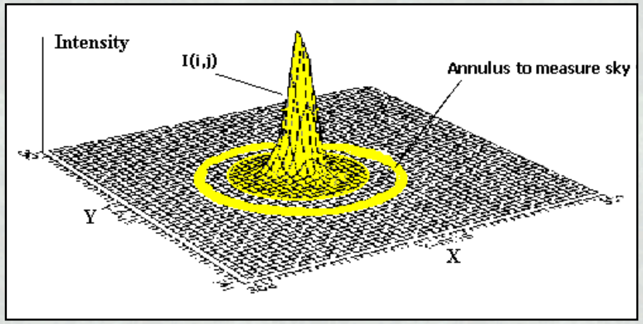
Observational Astronomy & Data Reduction

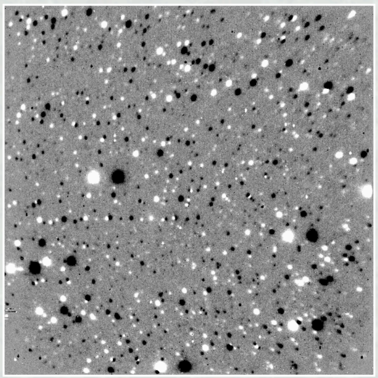












Karín Menéndez-Delmestre
Observatório do Valongo

Syllabus

I. Basics Concepts in Observational Astronomy:

- Telescopes
- coordinate systems
- Image Quality

II. Signal and Sources of Noise

- Detectors
- Poisson statistics
- shot noise
- sky
- Read noise
- dark current

III. Observing Strategies
& Planning your observing night

IV. Basics of Data Reduction

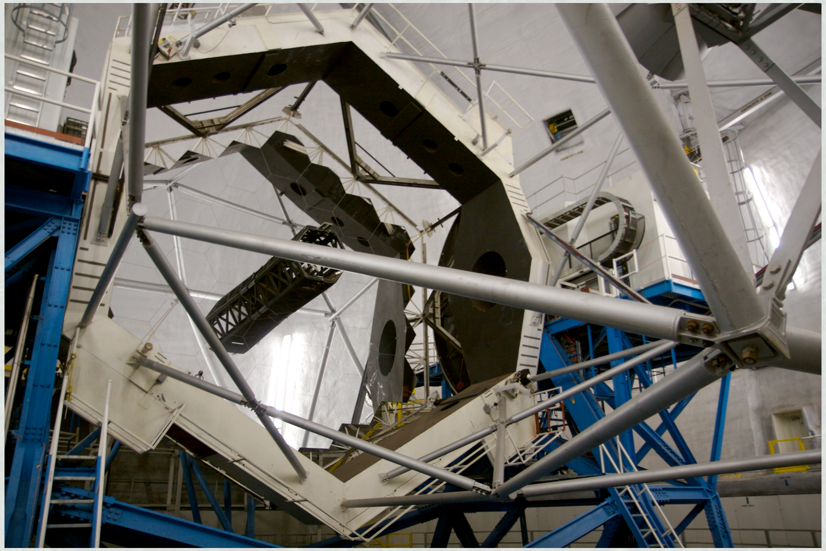
- Bias, Flats, Darks
- What, Why, When, How long and How many

V. Data Reduction

- Simple arithmetics!
- Bringing in the computer tools*
- Using basic IRAF routines or Python

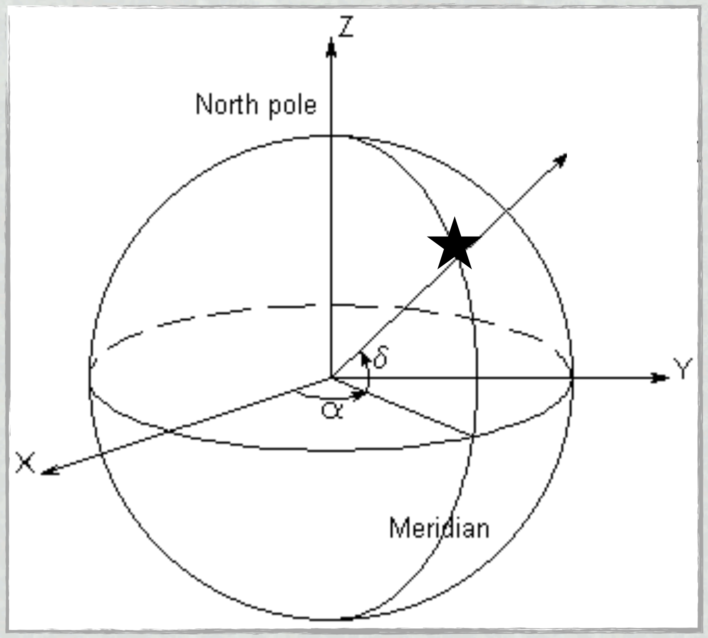
VI. Basic Aperture Photometry

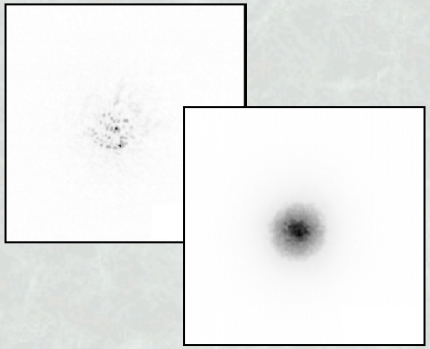
Observational Astronomy & Data Reduction



Lecture 1:

Telescopes
Coordinates
Image quality





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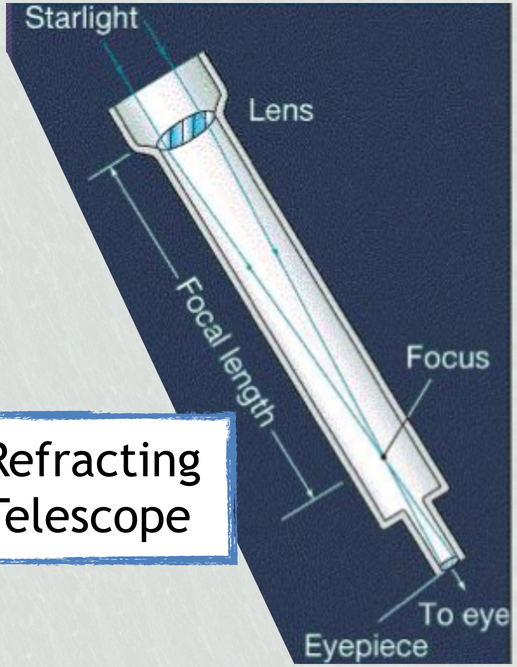
Telescopes

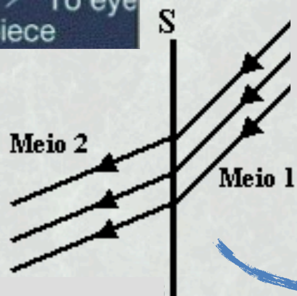
- Optical system that consists of:
  - Objetive: primary optical element (lens/mirror)



Refracting Telescope

A bit of telescope history…

- Invented in 1608 by Lippershey, the Netherlands
- First used for astronomical purposes by Galileu in1610 (Italy)



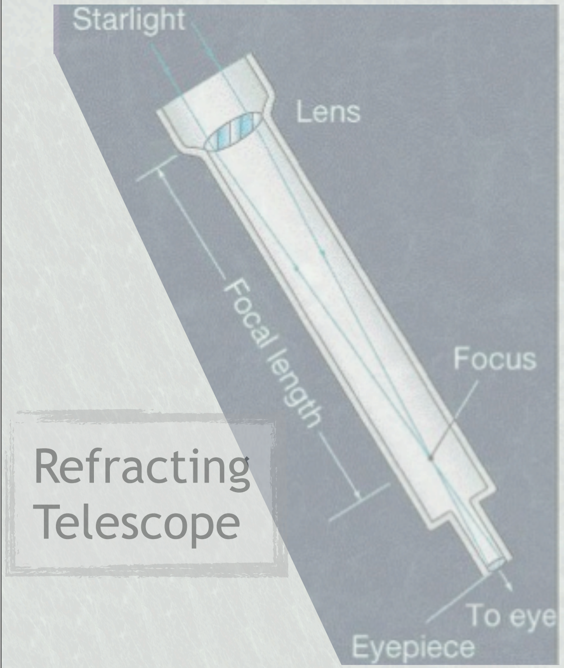
Incident light (parallel rays)

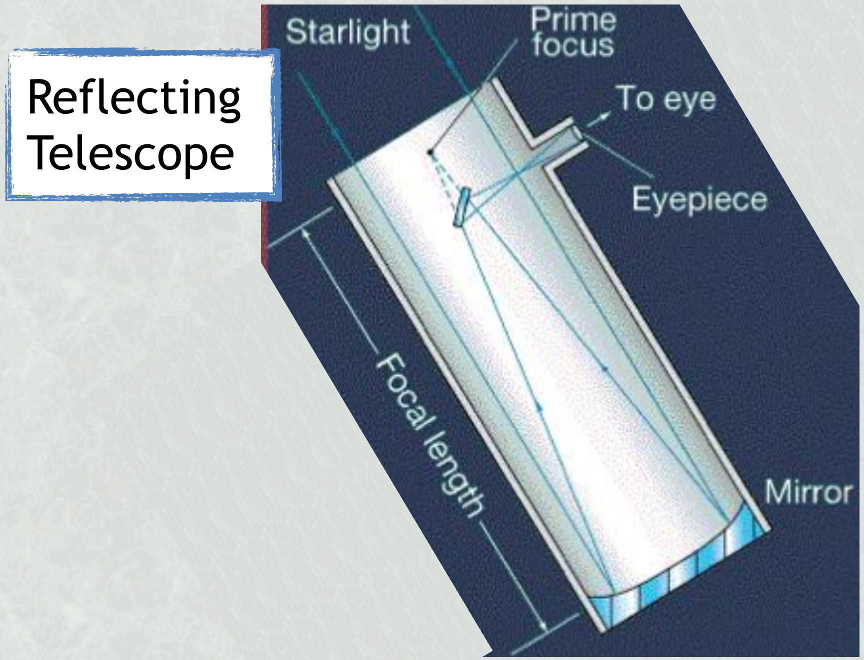
refracted rays

Refraction:
Incident light goes through *S* and continues to propagate. *S* separates two transparent media (air/water, water/glass, etc.)

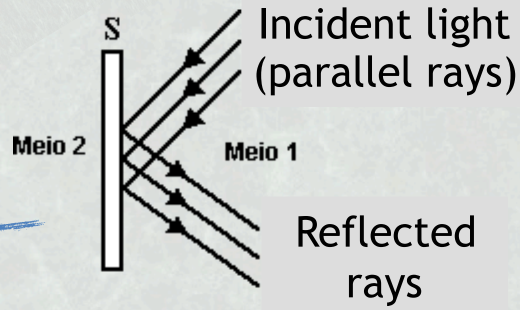
Telescopes

- Optical system that consists of:
  - Objective: primary optical element (lens/mirror)





<u>Reflection</u>:
Incident light is returns to the same medium. *S* is a well polished metallic-like (e.g., mirror) surface.



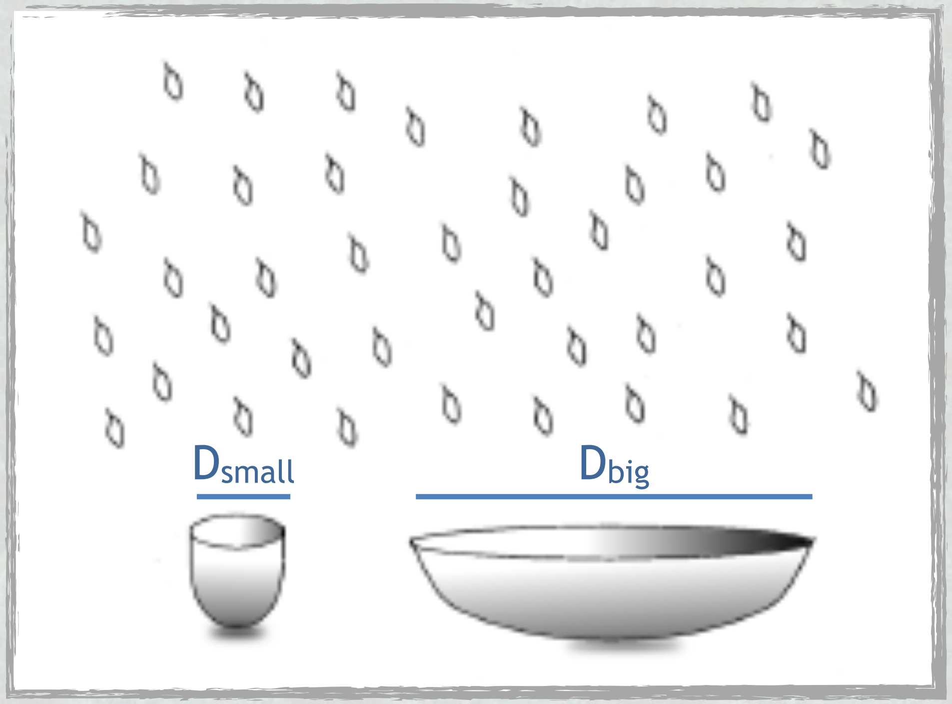
Telescopes

- Optical system that consists of:
  - Objective: primary optical element (lens/mirror)
    - What for? Capture light!
  - At the focal plane —> form an image!
    - A detector (e.g., CCD) → camera, or
    - eyepiece

Telescopes – basic functions

- Main function: collect photons
  - A telescope captures radiation intercepted by its aperture
  - ○ The bigger the aperture, the larger the quantity of photons collected

    —> collecting capacity is proportional to the area.



If photons of light are like raindrops, then telescopes are like buckets.

https://astrosociety.org/edu/publications/tnl/35/light2.html

Telescopes – basic functions

- Main function: collect photons
  - A telescope captures radiation intercepted by its aperture
  - ○ The bigger the aperture, the larger the quantity of photons collected
    —> collecting capacity is proportional to the area.
  - ○ Telescope size = aperture size = diameter of objective
    - In small telescopes, we measure the aperture in *mm* or *cm*
    - big ones, in *meters*!
  - ○ Can also think in terms of how long it takes to collect a fixed amount of energy
    - telescopes with larger apertures will collect in a shorter amount of time:

$$t_{big} = (D_{big}/D_{small})^2\ t_{small}$$

where t_{big} is the integration time for the bigger telescope with diameter D_{big}

Question #1

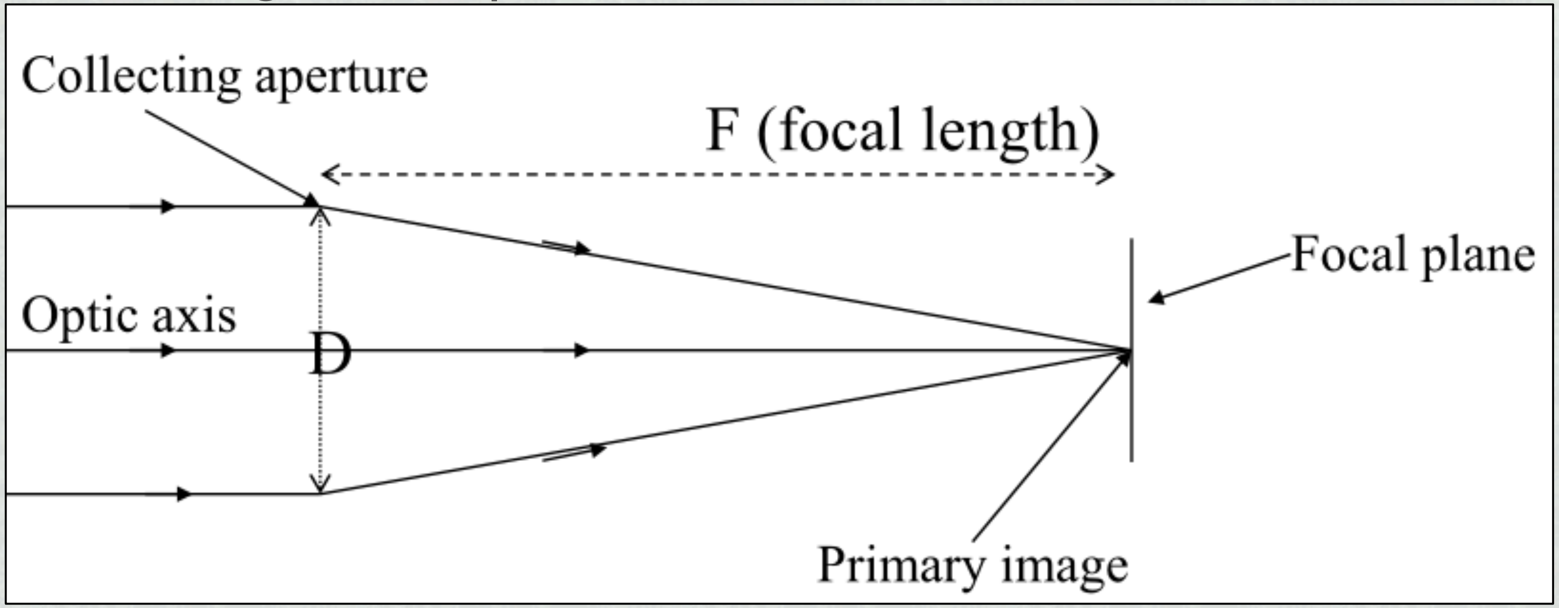
- How much faster can a 10m telescope collect light compared to a human eye?

Eye: ~7mm

Telescopes – optical properties

- Fundamental properties of any telescope:
  - Focal distance (F): distance (from the objective) at which the image of an infinitely-far away object is formed formada
    = distance between lens/mirror and the focal plane

Refracting Telescope



Note:
The optical path of a telescope is typically composed of various optical elements (lenses/mirrors); we refer to the *effective focal distance* for the whole optical system.

Telescopes – optical properties

- Fundamental properties of any telescope:
  - Focal distance (F): distance (from the objective) at which the image of an infinitely-far away object is formed formada
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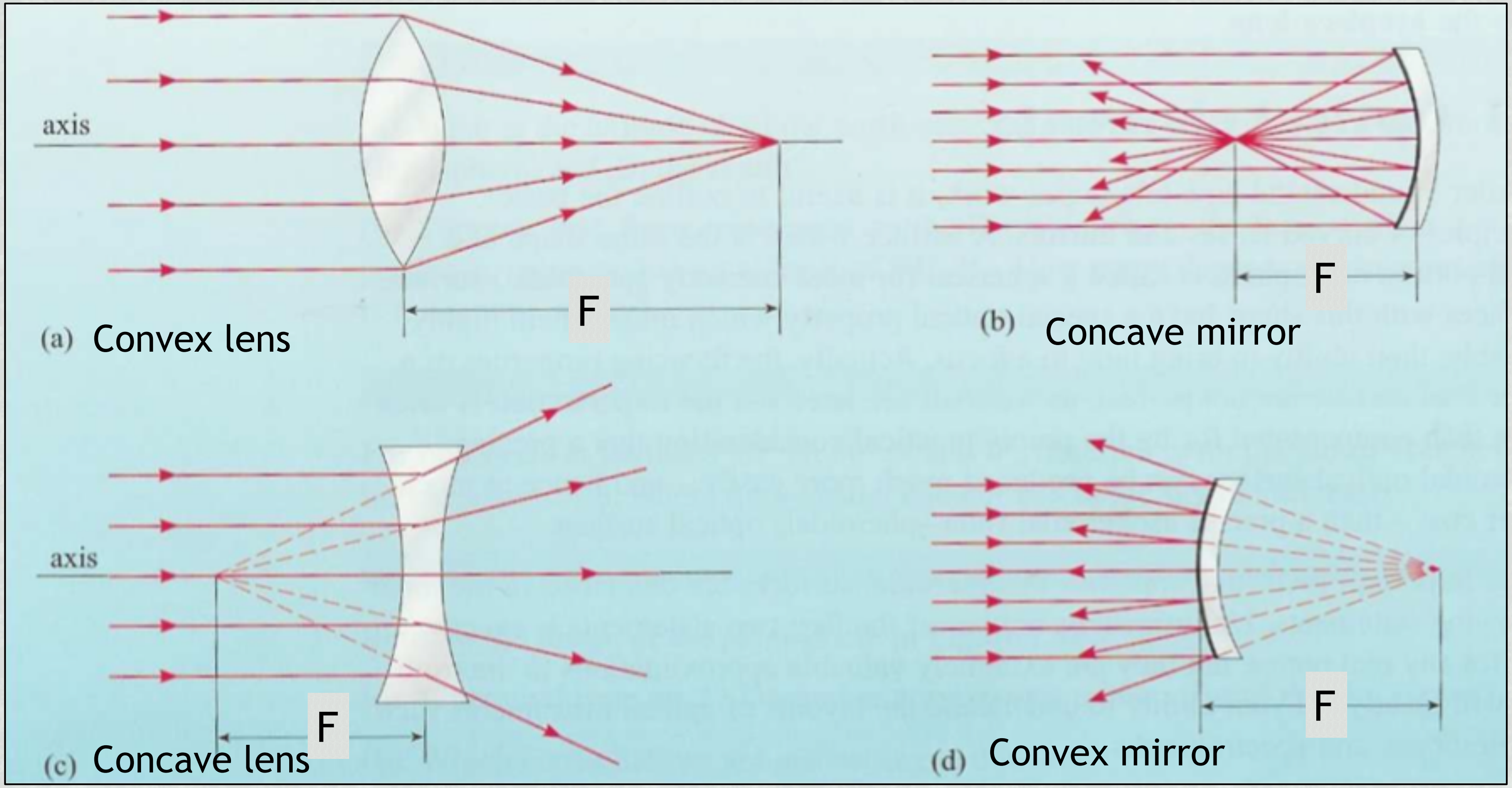

Telescopes – optical properties

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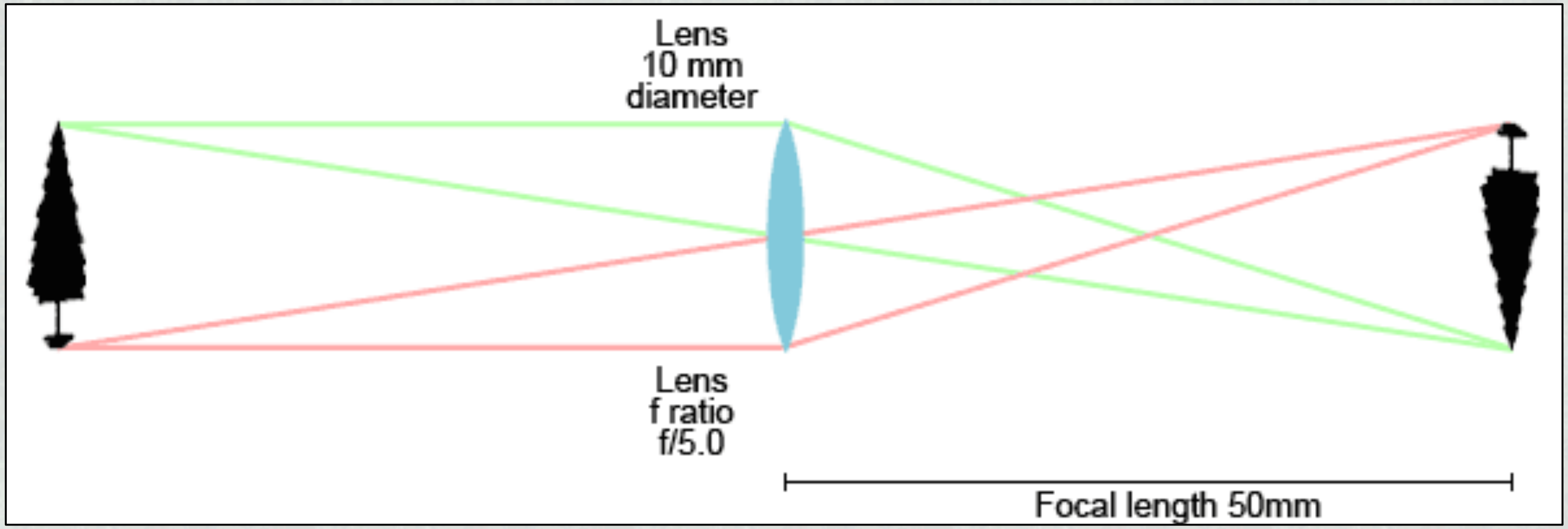
  - Aperture (A): diameter of the primary mirror/lens
  - Focal ratio (=F/A): *f*/number



http://digital-photography-school.com/photography-101-lenses-light-and-magnification

Telescopes – optical properties

- Fundamental properties of any telescope:
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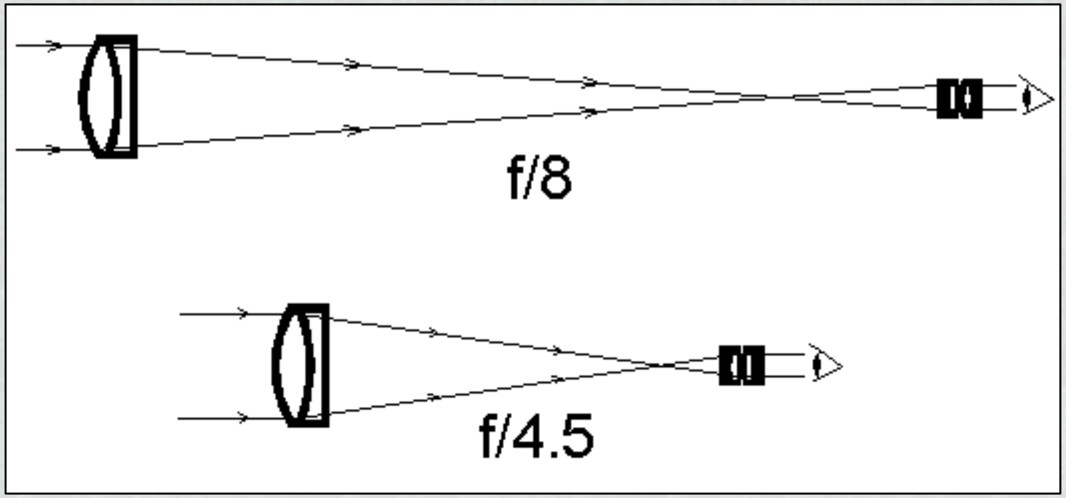
  - Aperture (A): diameter of the primary mirror/lens
  - Focal ratio (=F/A): *f*/number
    - The larger the focal distance, the larger the focal ratio (i.e., the larger the "number" in the expression *f*/number)



http://stargazerslounge.com/topic/150655-easy-way-to-understand-f-ratio-speed-of-a-scope

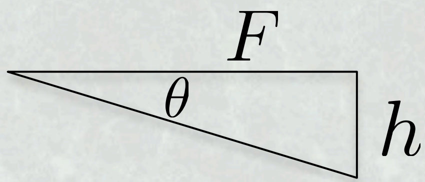
Telescopes – image size and FOV

- An object with an angular size θ (in radians) on the sky will form an image with linear physical size *h* (in *mm*) on the focal plane:

$$h = \theta_{radians}\,F$$

2π radians = 360 deg x 60’ x 60”

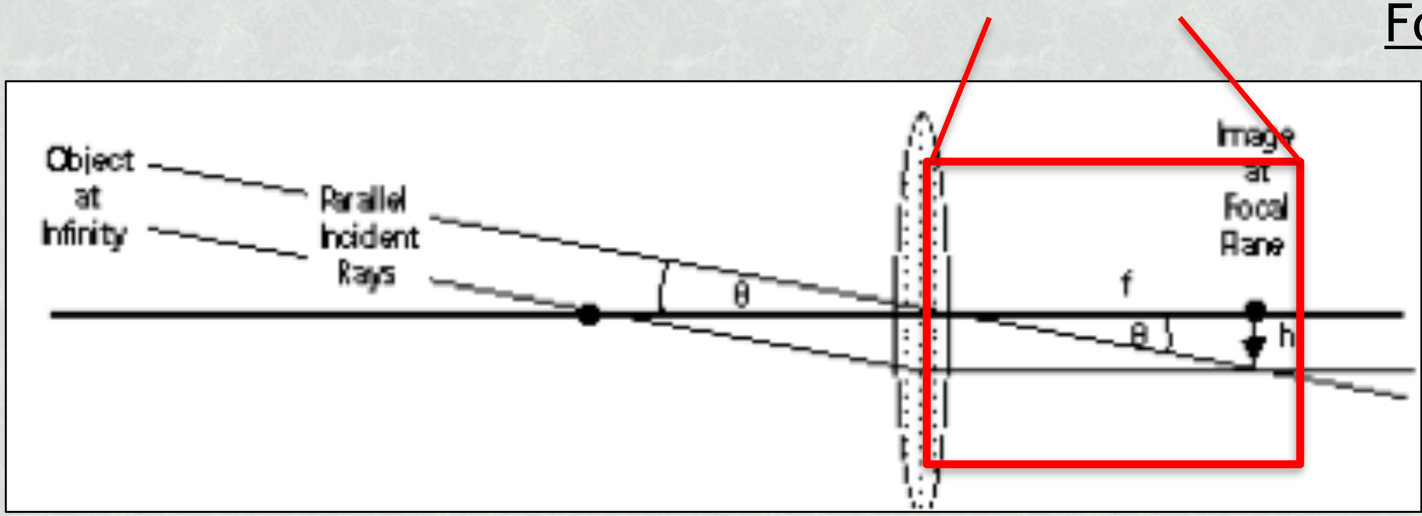
→ 1 rad = 206265”



$$tan\theta = h/F$$

For small θ:

$$F \times \theta = h$$



→ the larger the focal distance, the larger the physical size of the image

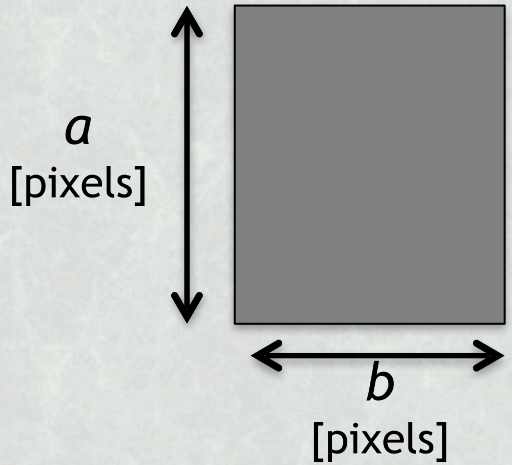
Telescopes – image size and FOV

- An object with an angular size θ (in radians) on the sky will form an image with linear physical size *h* (in *mm*) on the focal plane:

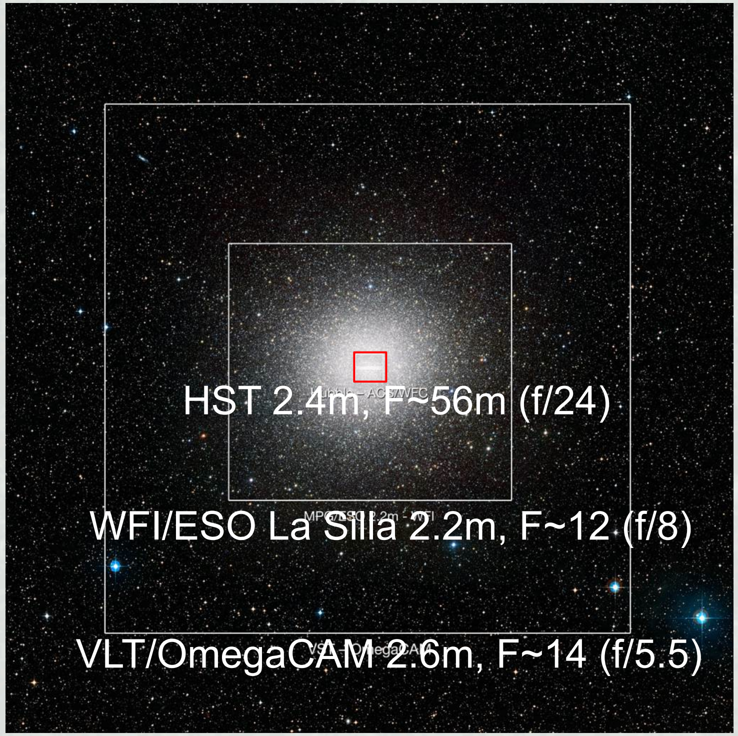
$$h = \theta_{radians} F$$

- If our detector (i.e., CCD) has physical dimensions *a* × *b*, the field of view (FOV) will be:

$$\theta_a \times \theta_b = (a \times b) / F^2$$



The larger the focal ratio, the smaller the FOV



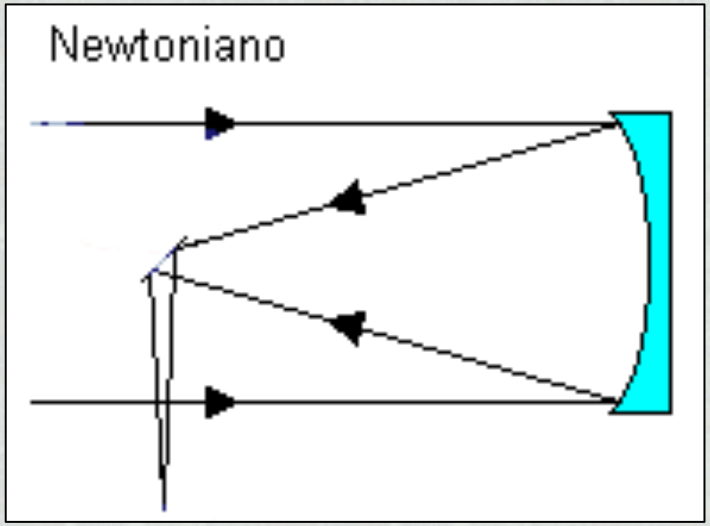
PR image globular cluster ESO1119i

http://cmarchesin.blogspot.com.br/2011/06/first-images-from-vlt-survey-telescope.html

Reflecting Telescopes — types

- **Newtonian:** simplest form of a reflecting telescope

- A flat secondary mirror redirects light towards telescope side, where eyepiece/detector is placed.
- Amateur astronomer's favorite: clean image (low in aberrations) and cheap!

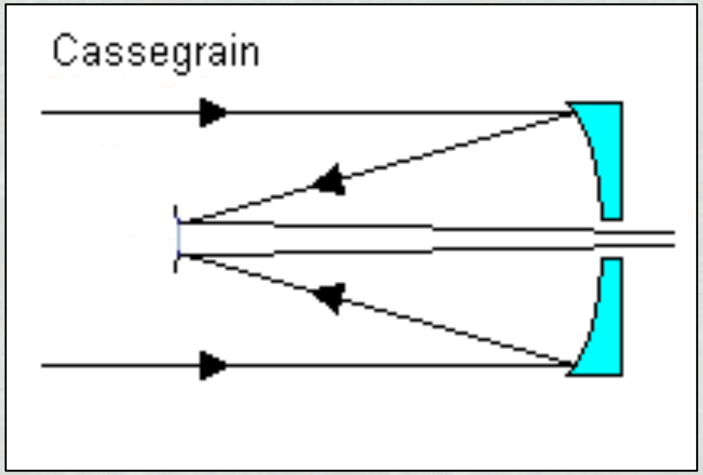


http://www.geocities.ws/saladefisica7/funciona/telescopio.html

Reflecting Telescopes — types

- Newtonian: simplest form of a reflecting telescope
- **Cassegrain**:

- A convex secondary mirror intercepts light reflected from a concave primary and sends it down a central opening in the primary mirror, where the detector is placed. This is the "cassegrain focus".
- The otherwise long light path folds onto a smaller telescope size —> allows for large aperture telescopes to be placed in smaller domes!
- Most frequently found in today's professional astronomical observatories.



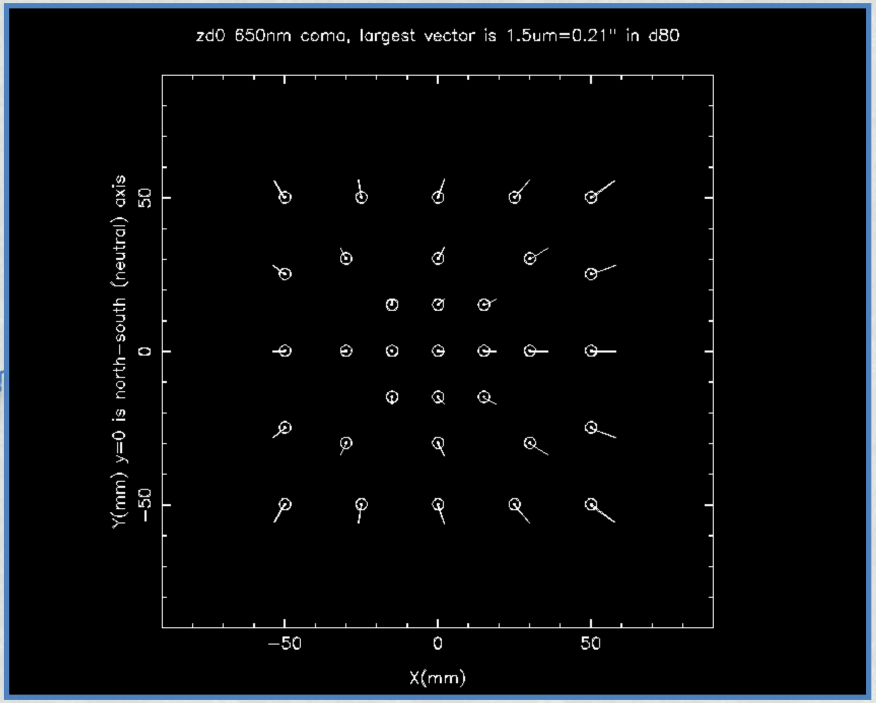
http://www.geocities.ws/saladefisica7/funciona/telescopio.html

Reflecting Telescopes — types

- Newtonian: simplest form of a reflecting telescope
- **Cassegrain:**

Variants:

- *Ritchey Chrétien* (e.g., Keck, Hubble)
    - shape of primary and secondary mirrors are different (hyperbolic) to minimize off-axis aberrations (e.g., coma)



- Happens in paraboloid mirrors —> light rays incident at an angle θ from the main optical axis do not all converge exactly at the same spot on the focal plane.

- Aberration results in a comet-like image extending from the focal point.

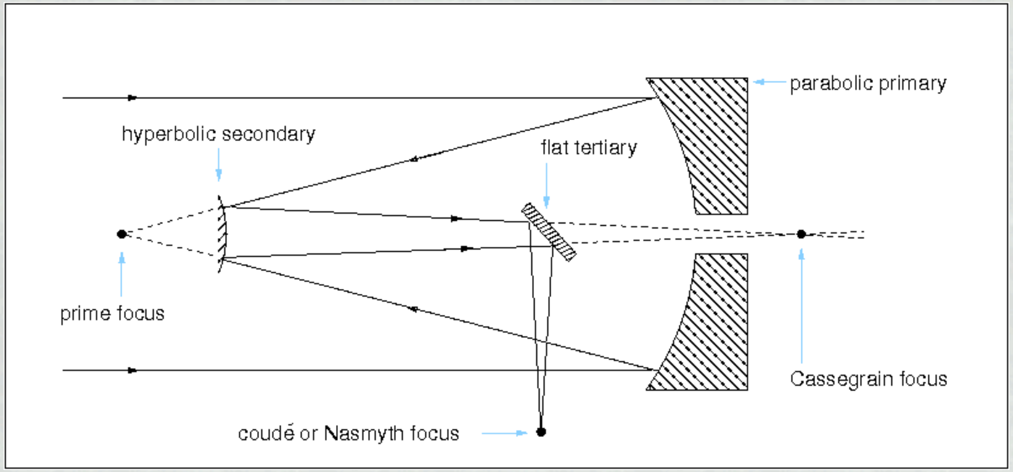
http://www.ctio.noao.edu/telescopes/opteng/optics.html

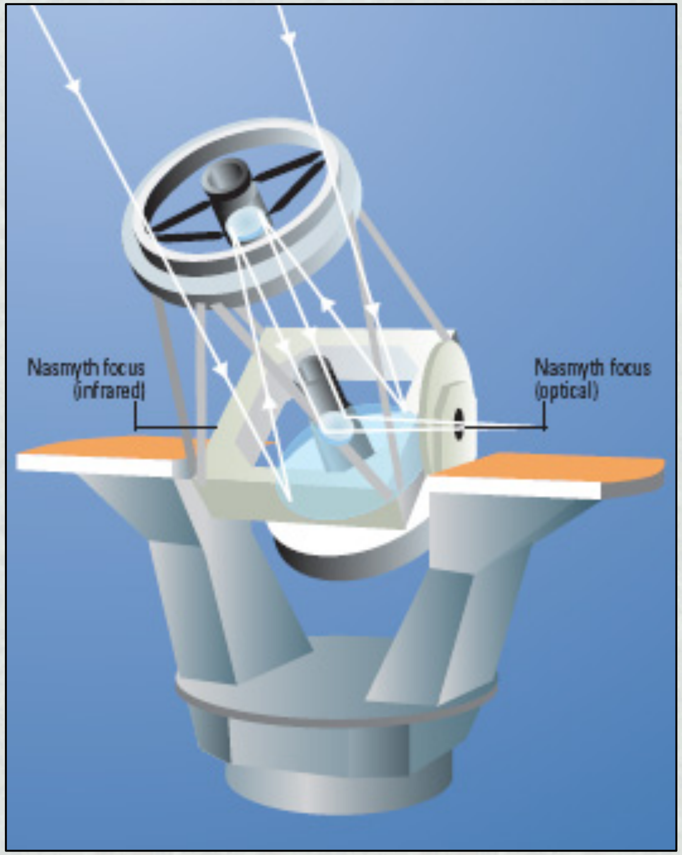
Reflecting Telescopes — types

- Newtonian: simplest form of a reflecting telescope
- **Cassegrain:**

Variants:

- *Ritchey Chrétien*
- *Nasmyth*
    - A tertiary mirror redirects light reflected from the secondary mirror to a lateral focus plane —> "Nasmyth focus"

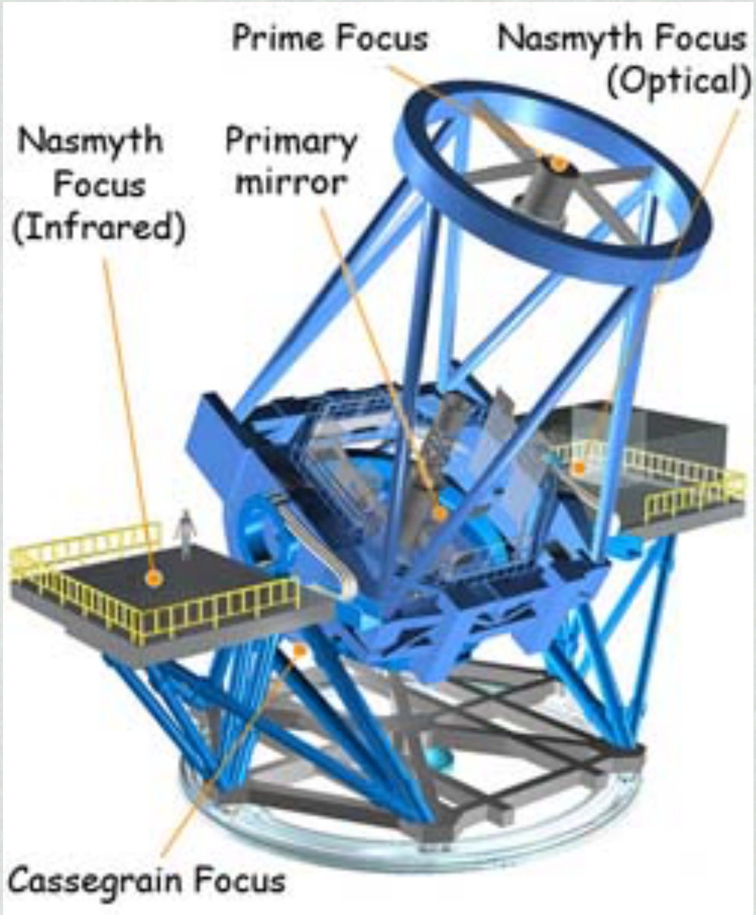




http://www.sozvezdiya.ru/eng/n.php

Telescopes — can host of many instruments!

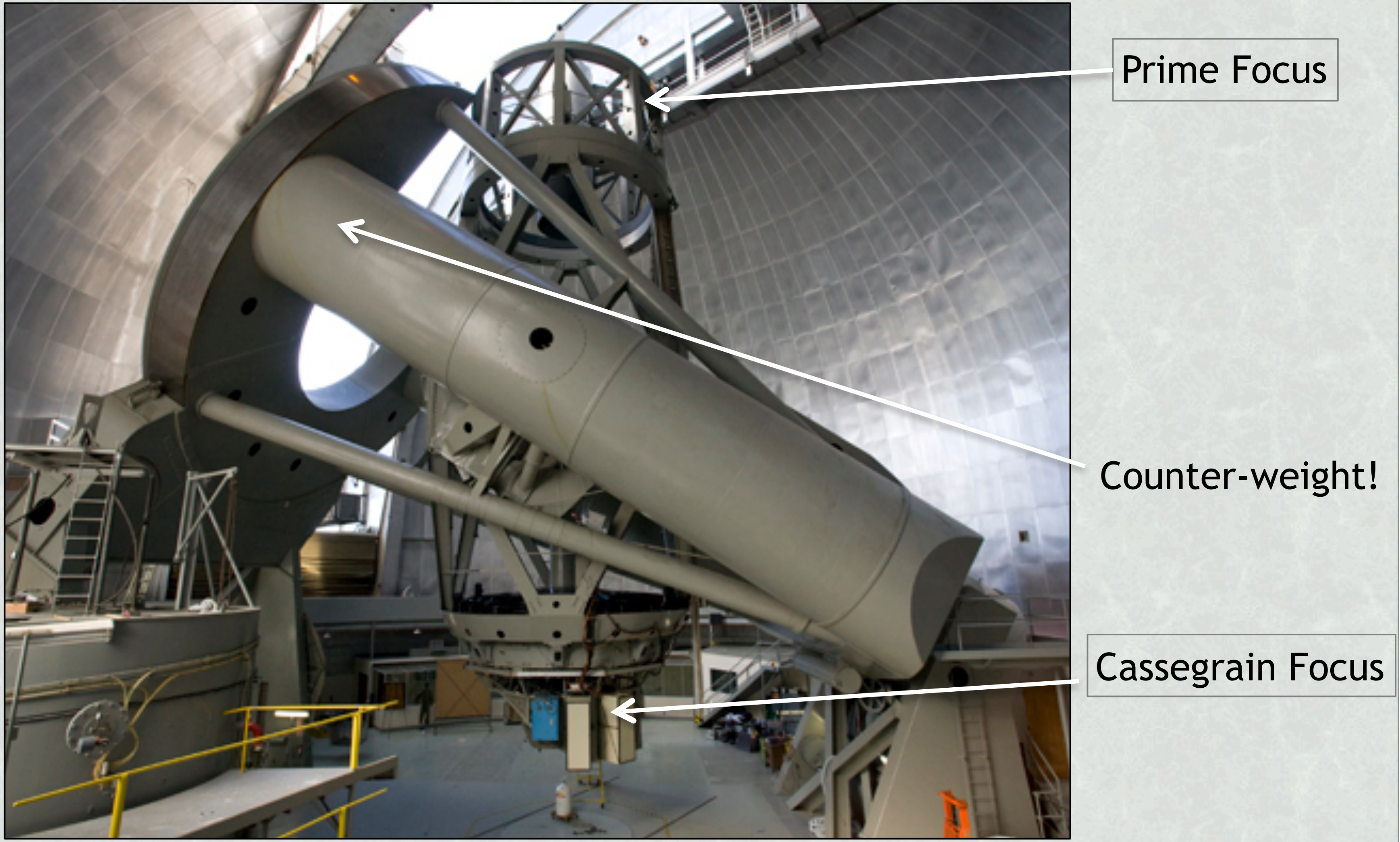
- A large quantity of instruments can be installed on a telescope:
  - Prime focus
  - Nasmyth focus
  - Cassegrain focus



Subaru Telescope

Telescopes — can host of many instruments!

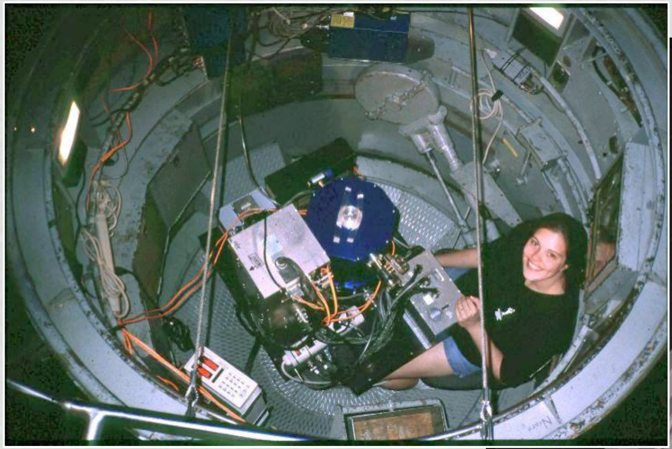
Hale (200-inch) Palomar Observatory

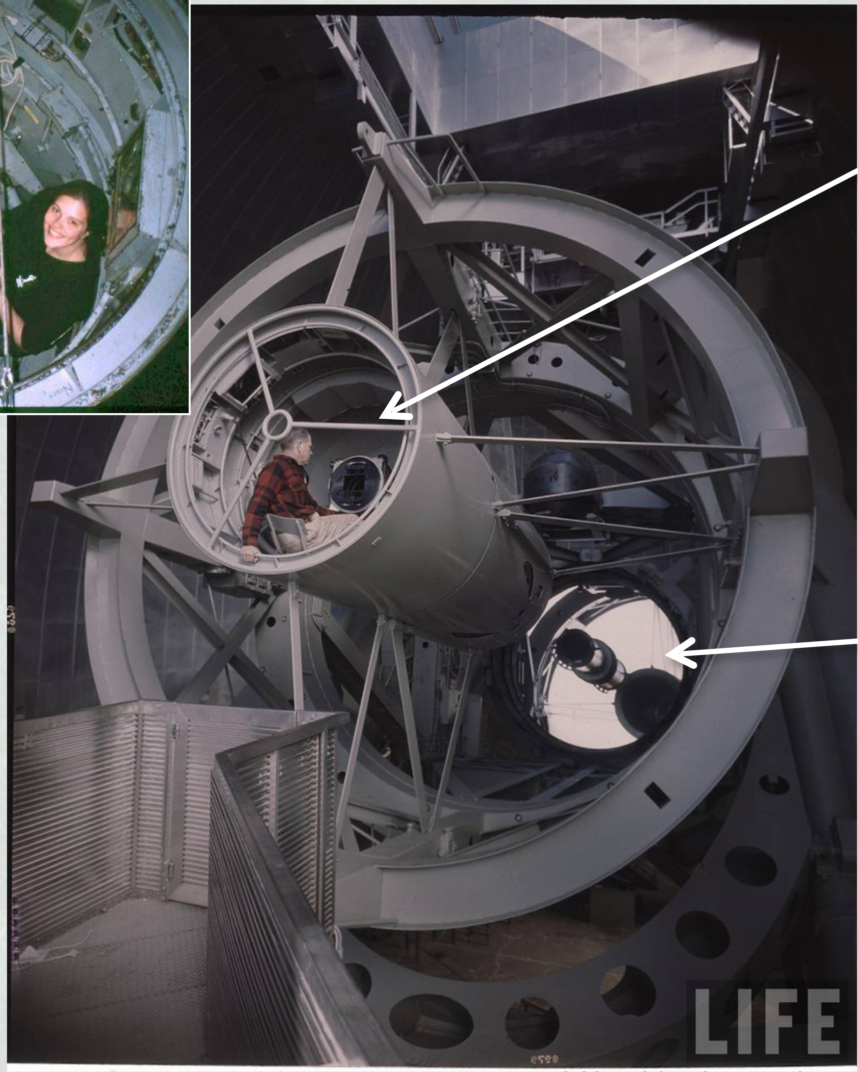


http://www.astro.caltech.edu/palomar/hale.html

Telescopes — can host of many instruments!

Hale (200-inch) Palomar Observatory





Prime Focus

Primary mirror

http://www.astrometrica.at/default.html?/images/200310.html

http://palomarskies.blogspot.com.br/2009/08/prime-time.

Telescopes — can host of many instruments!

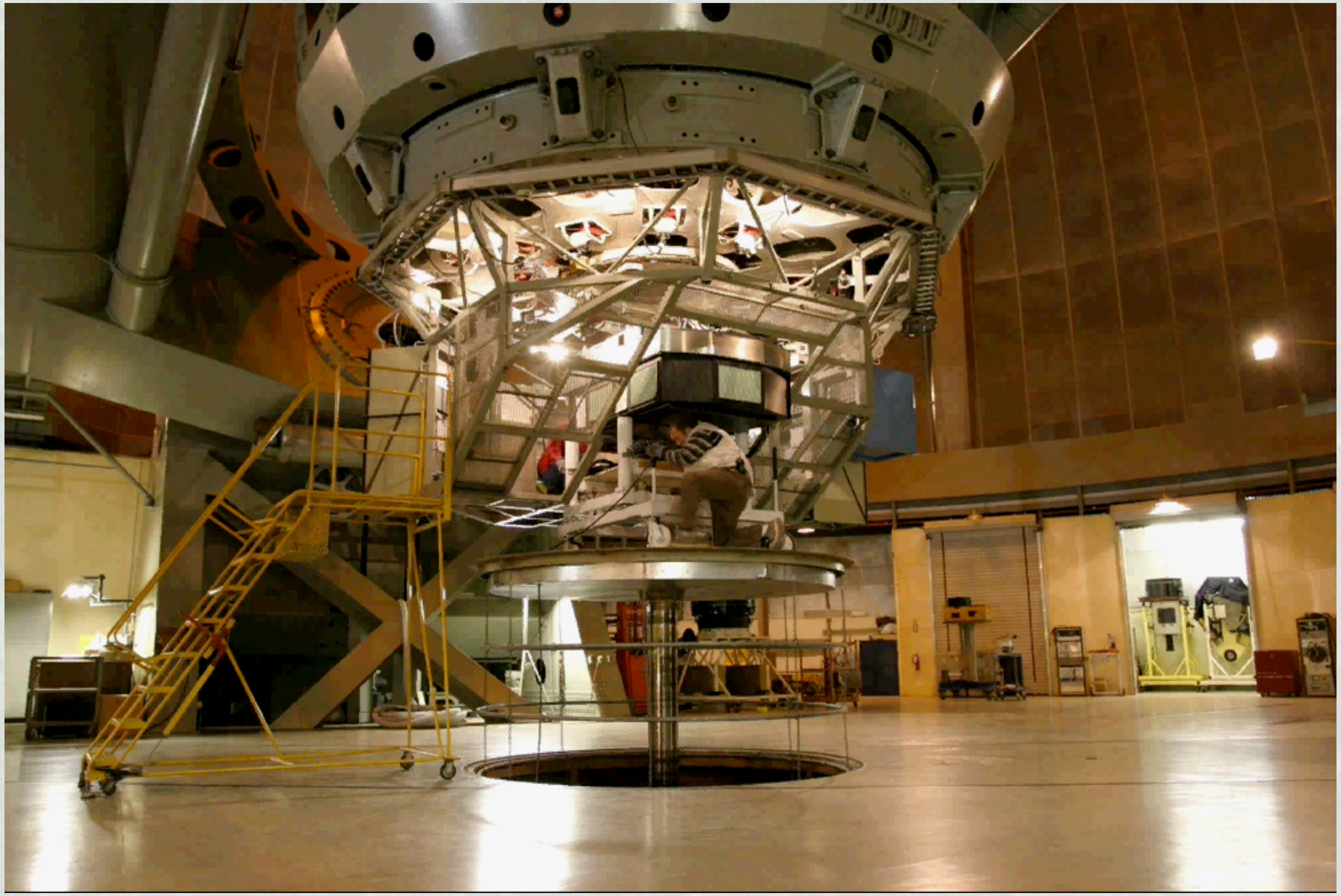
Hale (200-inch) Palomar Observatory

http://www.aip.org/history/cosmology/ideas/hubble.htm

Telescopes — can host of many instruments!

Hale (200-inch) Palomar Observatory

Installing AO system on Cassegrain focus

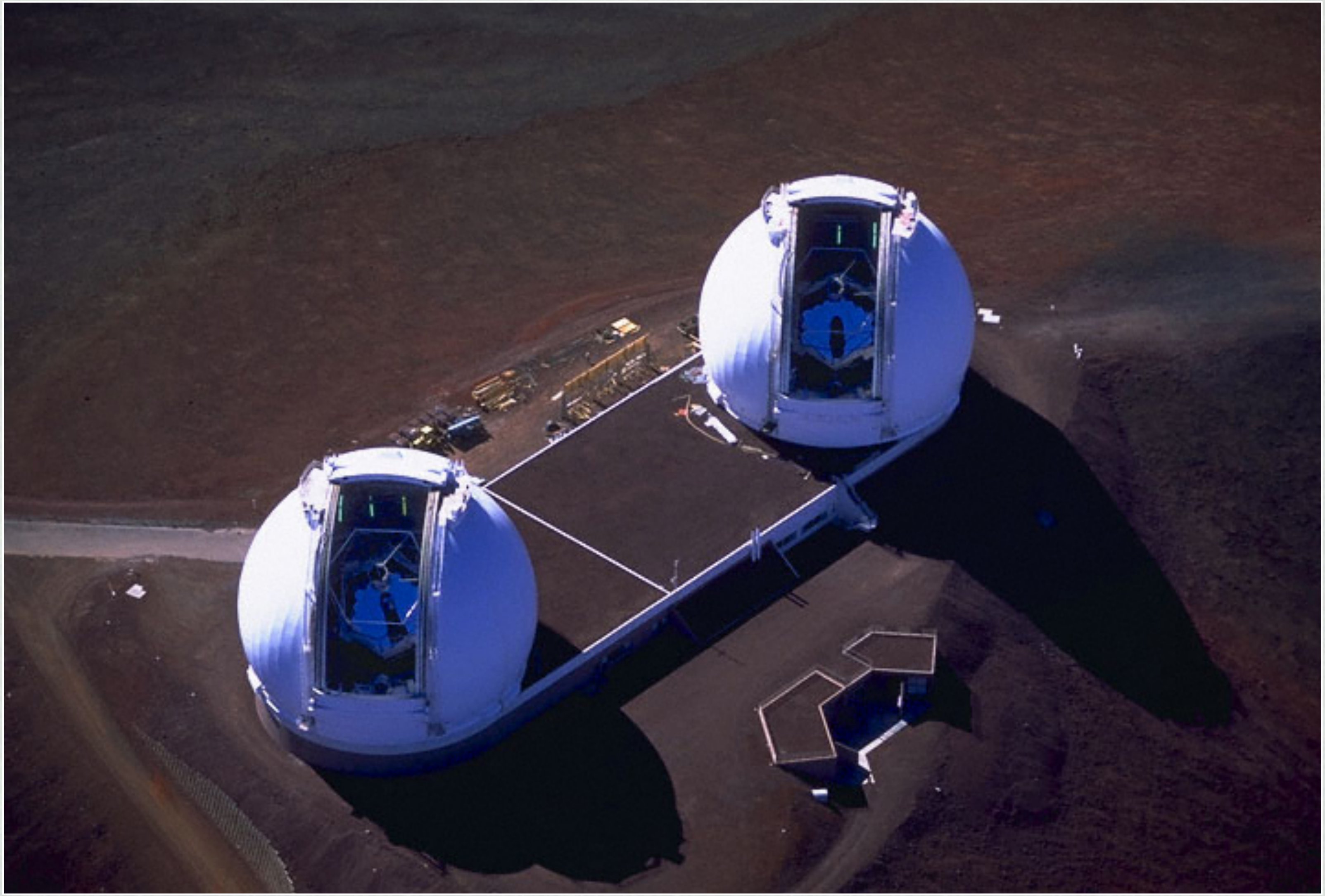


Being close to the ground, the Cassegrain focus is a conveniente site to place/change instruments.

http://www.astro.caltech.edu/palomar/hale.html

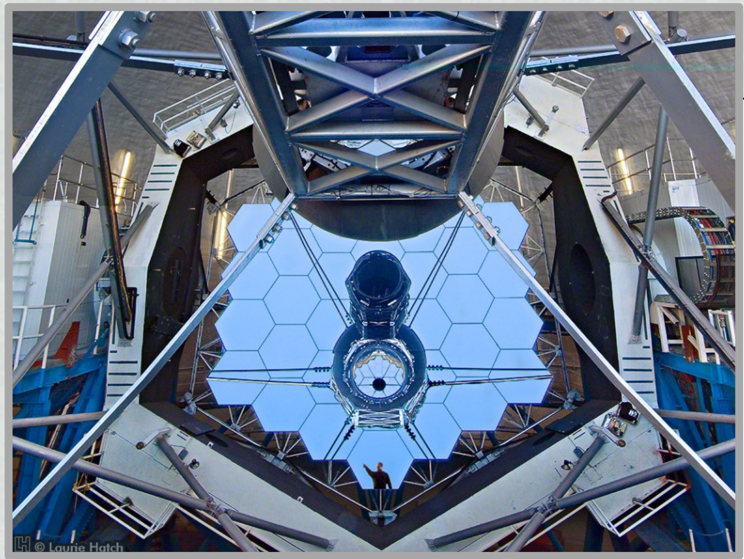
Telescopes — can host of many instruments!

Keck Telescopes (2 x 10m)

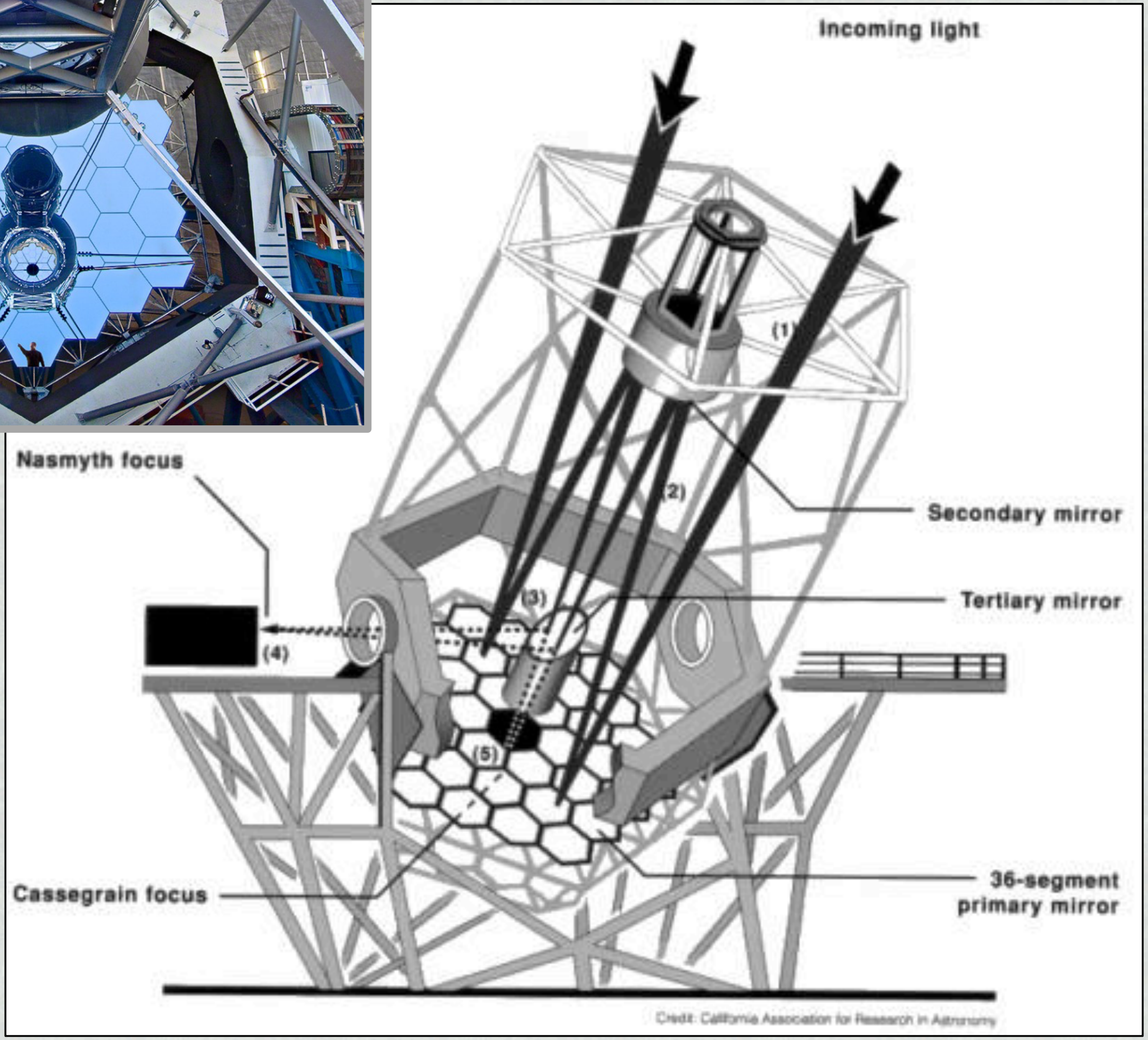


http://www.ifa.hawaii.edu/images/aerial-tour/kecks.html

Telescopes — can host of many instruments!



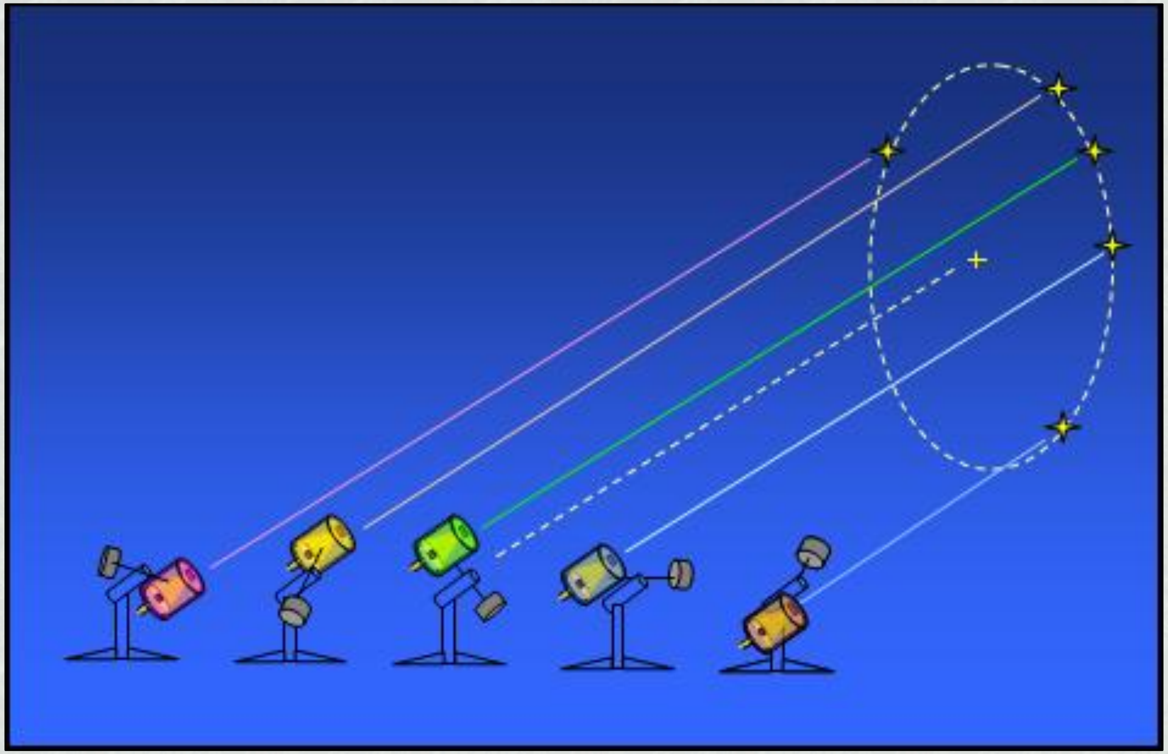
Keck Telescopes (2 x 10m)



http://www.astro.ljmu.ac.uk/courses/phys134/scopes.html

Telescopes — equatorial and azimuth mounts

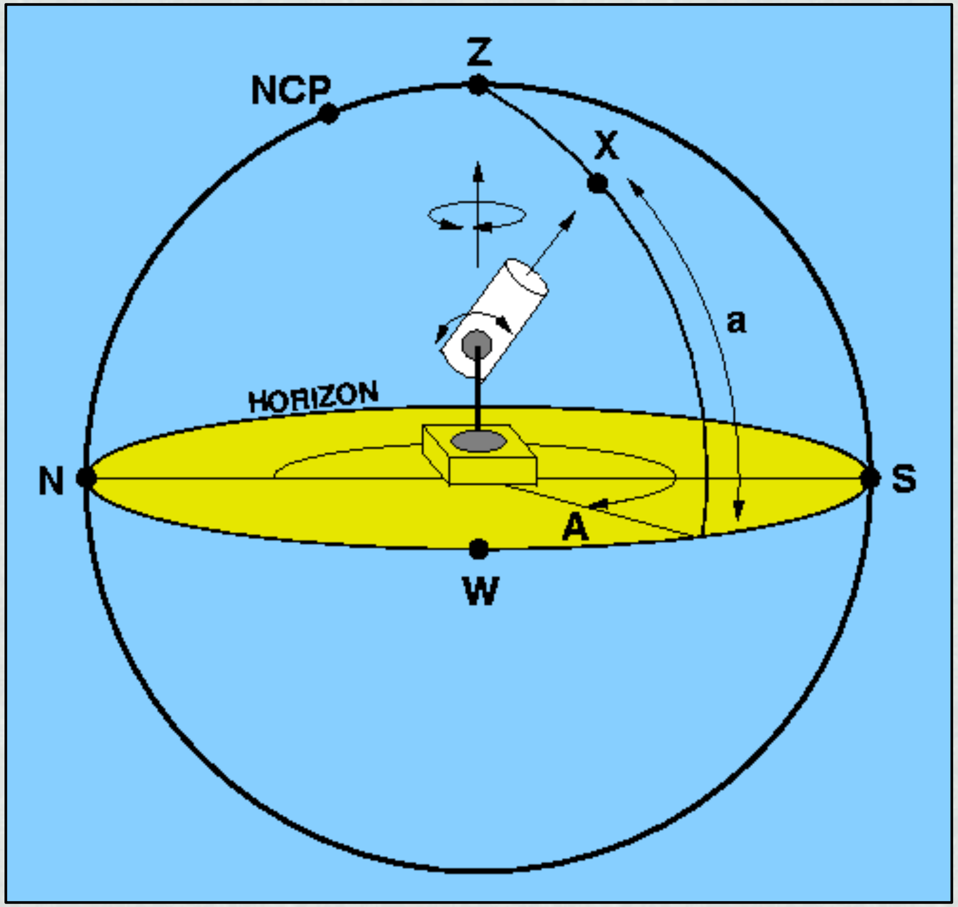
- **Equatorial mount:**
  - Typically used in medium-sized telescopes
  - One of the axes is parallel to the Earth's rotation axis
  - Only need to rotate to track the daily movement of the object.



http://www.astronomyasylum.com/telescopemountstutorial.html

Telescopes — equatorial and azimuth mounts

- **Alt-azimuth mount:**
  - Typically used in large professional telescopes
  - 2 axis: vertical and horizontal → **mechanically more stable than the equatorial mount**
    - Rotation about the vertical axis varies the azimuth
    - Rotation about the horizontal axis varies the altitude
  - Need to rotate both axes to track objects



Vik Dhillon's Lecture notes
University of Sheffield, UK
http://www.vikdhillon.staff.shef.ac.uk/teaching/phy217/telescopes/phy217_tel_altaz.html

Telescopes — pointing challenges

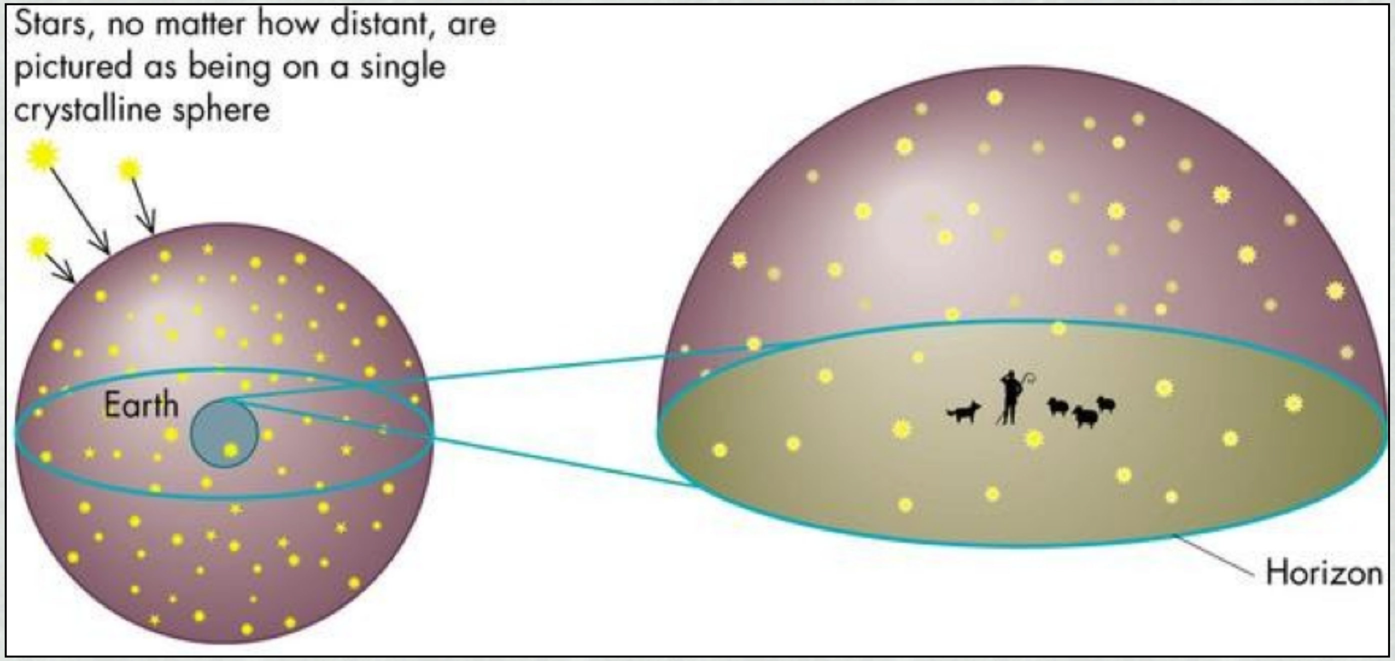
- Pointing and guiding are not perfect in any mount:
  - Alignment of rotation axes
  - Mechanical flexure of the physical structure (gravity!)
  - Gearing errors
  - Atmospheric refraction

—> Real-time corrections on the pointing are made by *guiders*

- a parallel tracking system that follows bright stars chosen as *guides*
- Crucial for long integrations!

Coordinate system — the celestial sphere

- Need a system to define the positions of celestial bodies
  - Independent of the distance!
- A 2D view (a projected view) of the night sky
- Celestial Sphere: not real, but a useful concept!
  - Consider as though stars where stickers on a large sphere, with Earth at its center



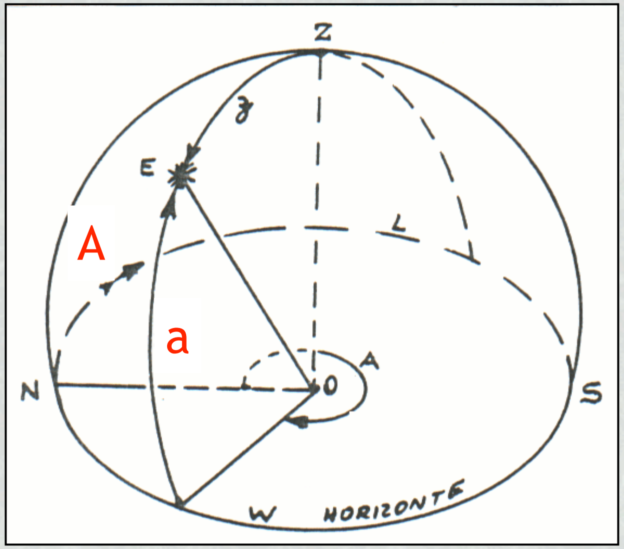
Coordinate system — the celestial sphere

- To define the position of a point on a sphere, need two angles

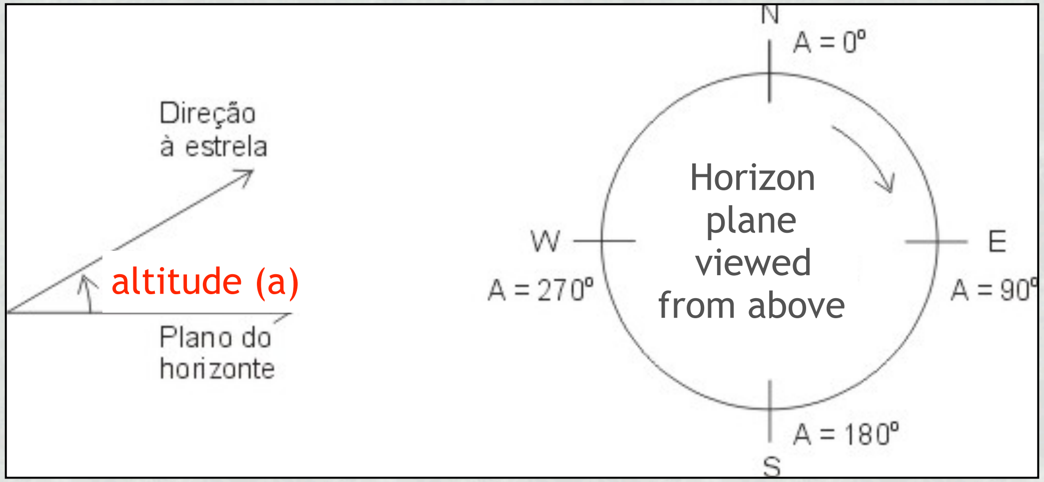
(1) Horizontal system: *alt* and *azimuth* – most intuitive system for an observer on the Earth's surface.

- Altitude (*a*) or elevation: ∡ above observer's horizon
- Azimuth (A): ∡ that defines distance between a reference point and the projection of the celestial body onto the horizon's plane.
  - Reference point: North (∡ increases towards East)

http://www.ebah.com.br/content/ABAAABuFwAI/astronomia-posicao



altitude < 0 corresponds to objects below the horizon



http://www.if.ufrgs.br/oei/santiago/fis2005/textos/sistcrds.htm

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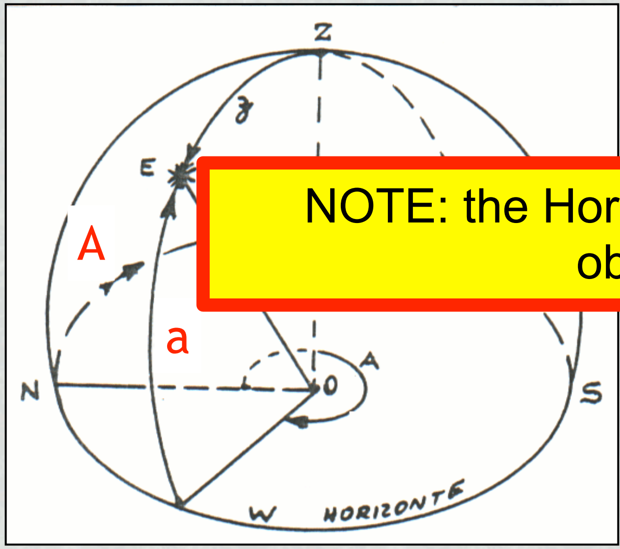
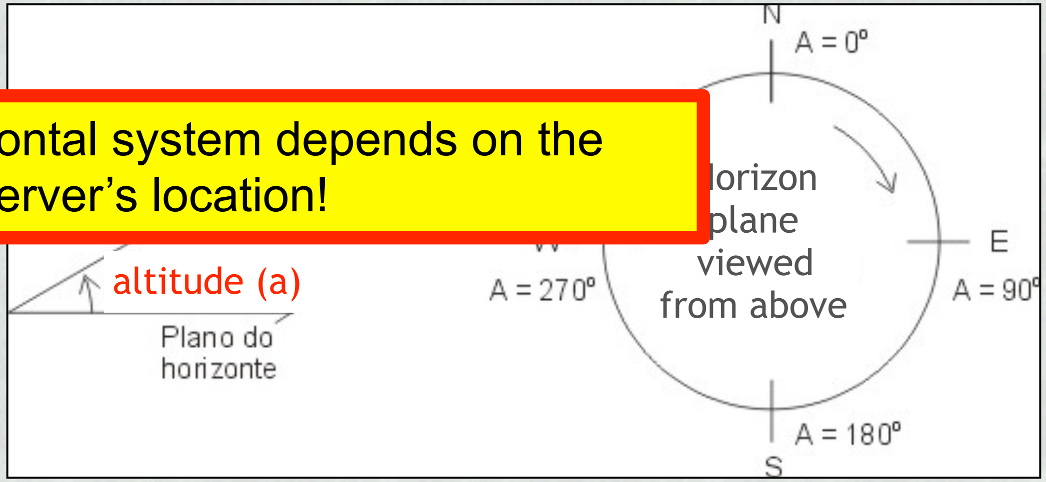
    - Reference point: North (∡ increases towards East)

altitude < 0 corresponds to objects below the horizon



http://www.ebah.com.br/content/ABAAABuFwAI/astronomia-posicao

NOTE: the Horizontal system depends on the observer's location!



http://www.if.ufrgs.br/oei/santiago/fis2005/textos/sistcrds.htm

Question #2

- Consider the Sun’s altitude just before (and just after) the sunset.
    a. Does the sky become dark when the Sun sets? Immediately? A bit later?
    b. Define the concept of “Astronomical Twighlight"
    c. Why is this concept important when observing?

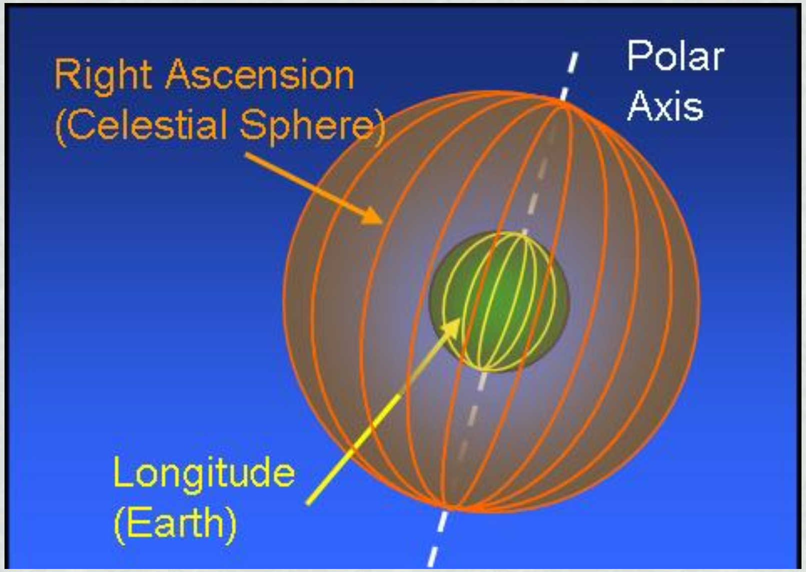
Coordinate system — the celestial sphere

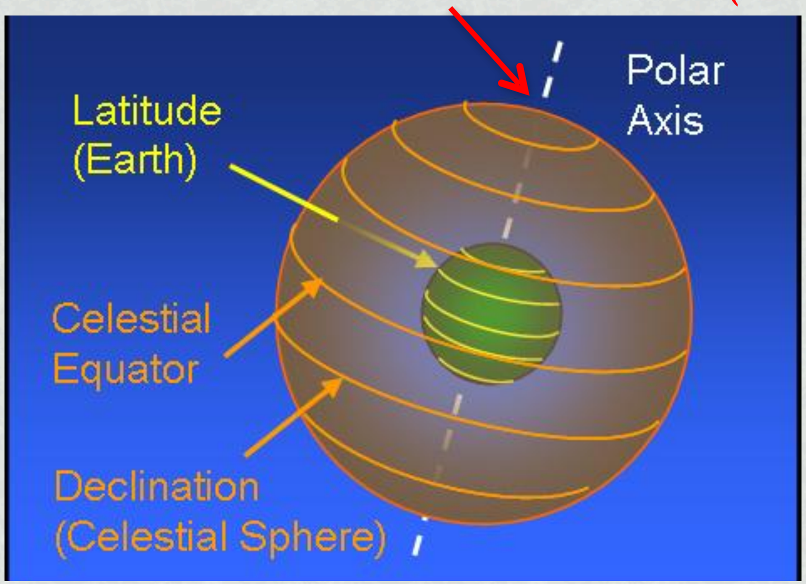
- To define the position of a point on a sphere, need two angles

  (1) Horizontal system: *alt* and *azimuth*

  (2) Equatorial system: *declination (DEC) and right ascension (RA)*

  - Similar to the latitude system on Earth, where the plane of reference is the Earth's equator; in the equatorial system we have the celestial equator (an extension of the Earth's equator)



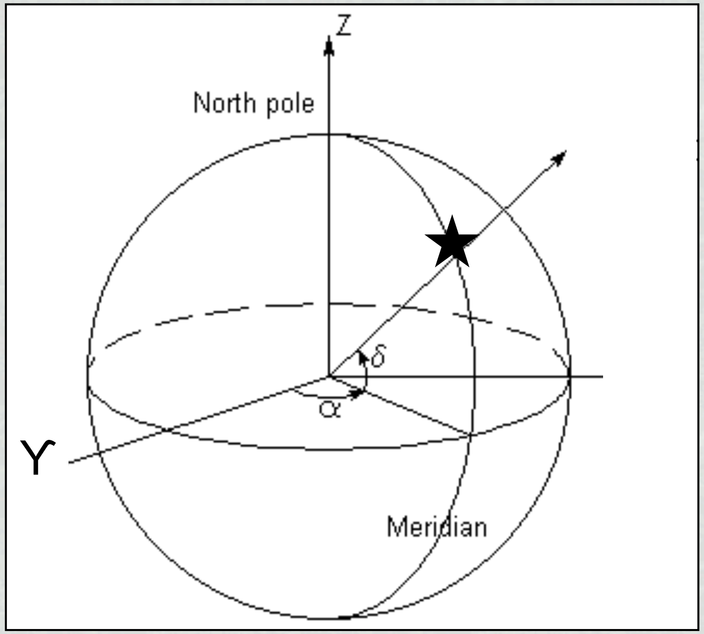


Coordinate system — the celestial sphere

- To define the position of a point on a sphere, need two angles

  (1) Horizontal system: *alt* and *azimuth*

  (2) Equatorial system: *declination (DEC) and right ascension (RA)*



http://www.astro.cornell.edu/~berthoud/alpsat/chapter4a.html

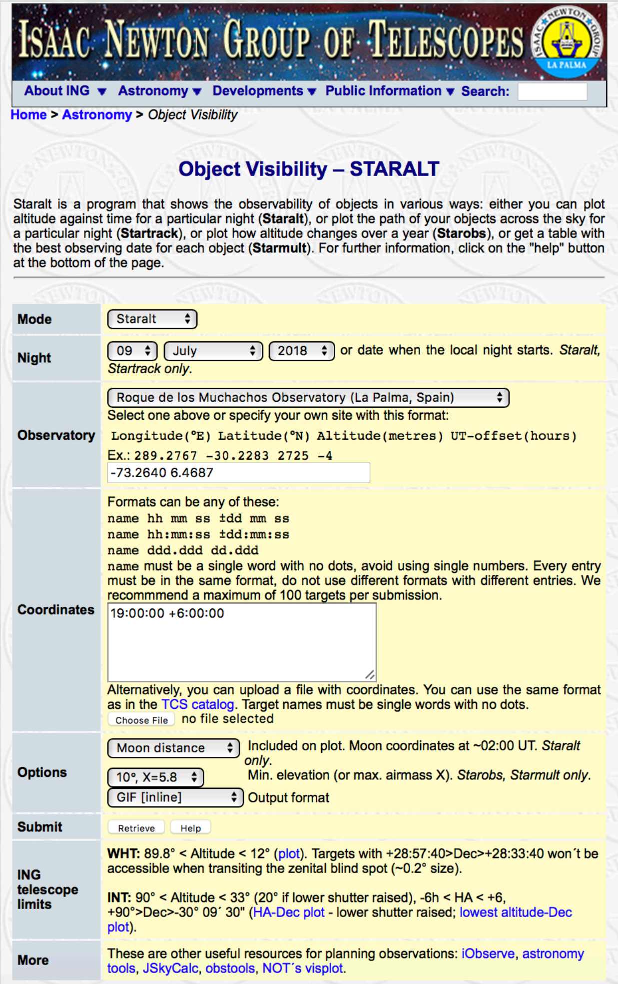
- Declination (δ): ∡ above celestial equator
- Right Ascension (α): ∡ from a reference point and the projection of the celestial object onto the equatorial plane
  - Reference point: “Vernal point” (ϒ)
  - ∡ increases towards the East

Vernal point: This is the Sun’s position on the March equinox, when the Sun crosses the equatorial plane towards the North.

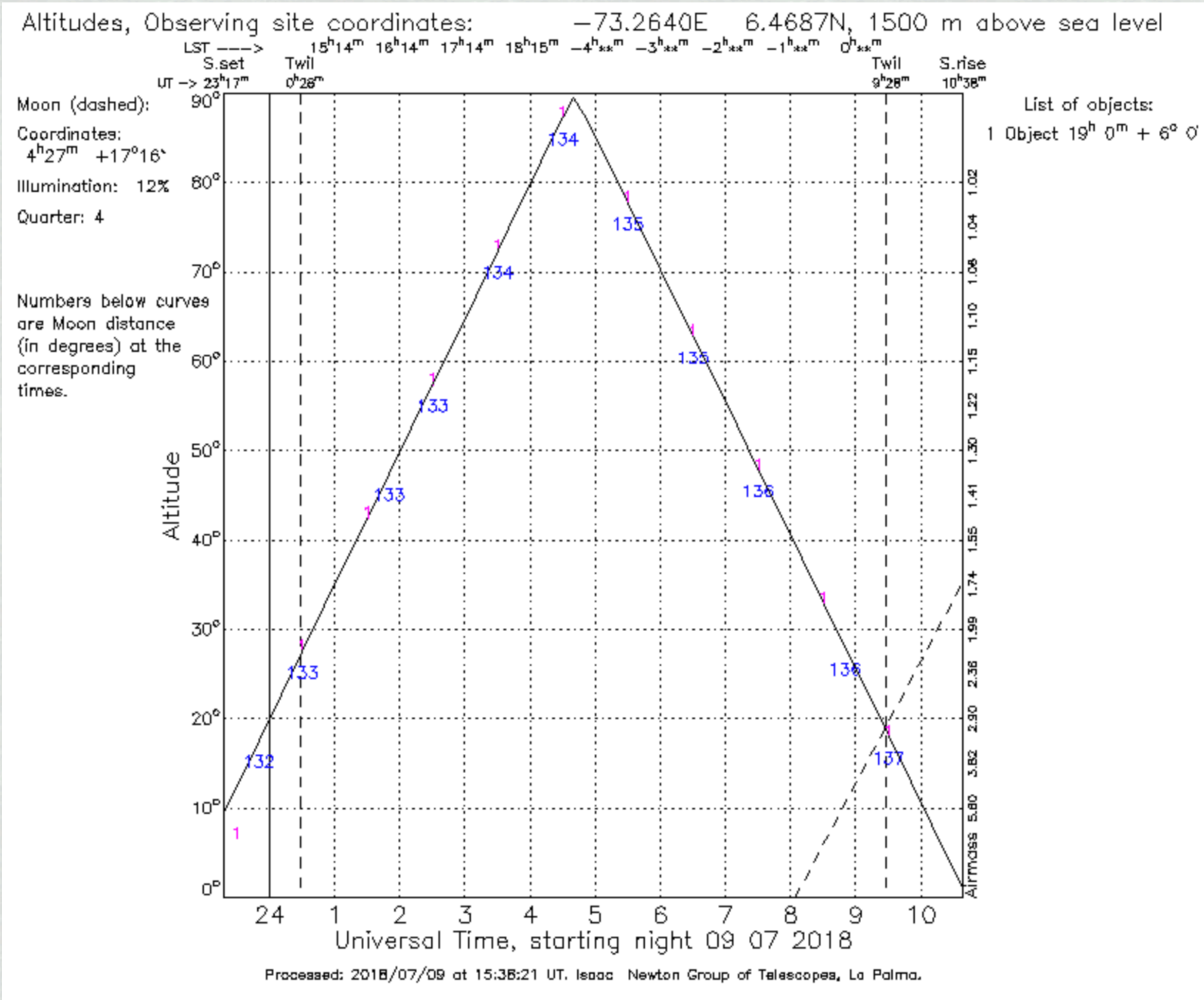
Question #3

- What are the approximate RA/DEC coordinates of a celestial body that would be ideal to observe tonight?

Socorro's latitute: ~6.5°N
Today's date: July 9, 2018



Question #3



19:00:00.00 +06:00:00.00

StarAlt:

http://catserver.ing.iac.es/staralt/

Question #3

- What are the approximate RA/DEC coordinates of a celestial body that would be ideal to observe tonight?

Socorro's latitute: ~6.5°N
Today's date: July 9, 2018

19:00:00.00 +06:00:00.00

Accessible RA range depends on time of the year

Accessible DEC range depends on telescope's latitude

Coordinate system — the celestial sphere

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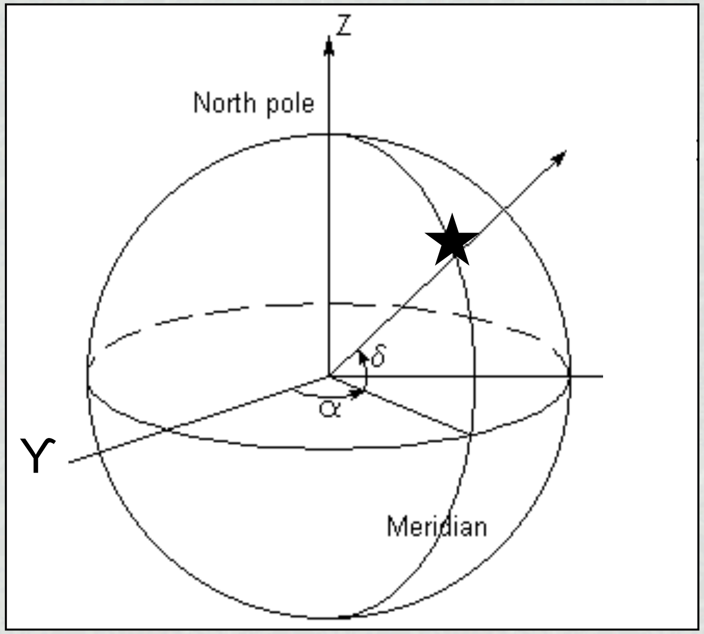

- Declination(δ) in degrees:

  dd:mm:ss.ss

  degrees : arcminutes : arcseconds

  δ > 0 Northern hemisphere;

  δ < 0 Southern hemisphere

- Right ascension (α) in hours:

  hh:mm:ss.ss

  hours : minutes : seconds

Note: RA is typically expressed as hh:mm:ss.ss. However, at times we can also find it in terms of decimal hours (i.e., hh.hh) or degrees (i.e., dd.dd).

http://www.astro.cornell.edu/~berthoud/alpsat/chapter4a.html

Coordinate system — the celestial sphere

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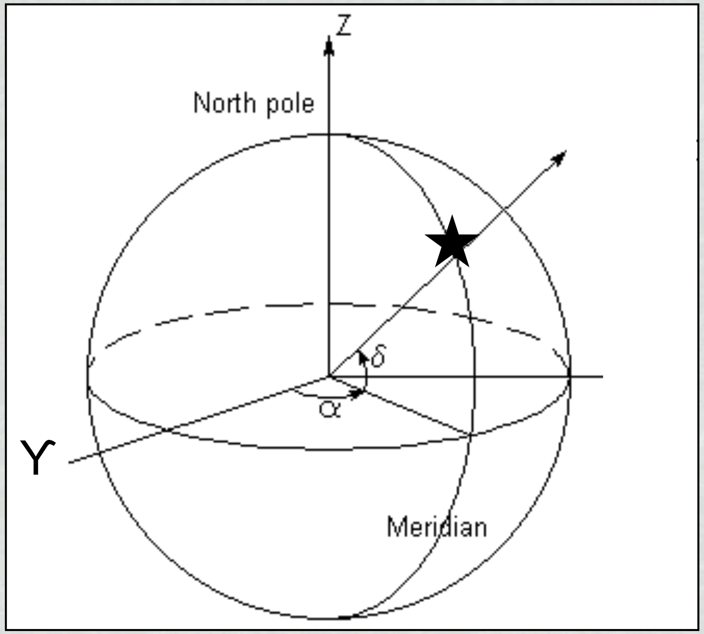

http://www.astro.cornell.edu/~berthoud/alpsat/chapter4a.html

- Declination(δ)
- Right ascension (α)

✳ Reminder: The angular distance between two points with the same declination is not simply the difference in RA.

✳ factor of cos(DEC)!

✳ RA is measured on the plane of the equator.

Coordinate system — the celestial sphere

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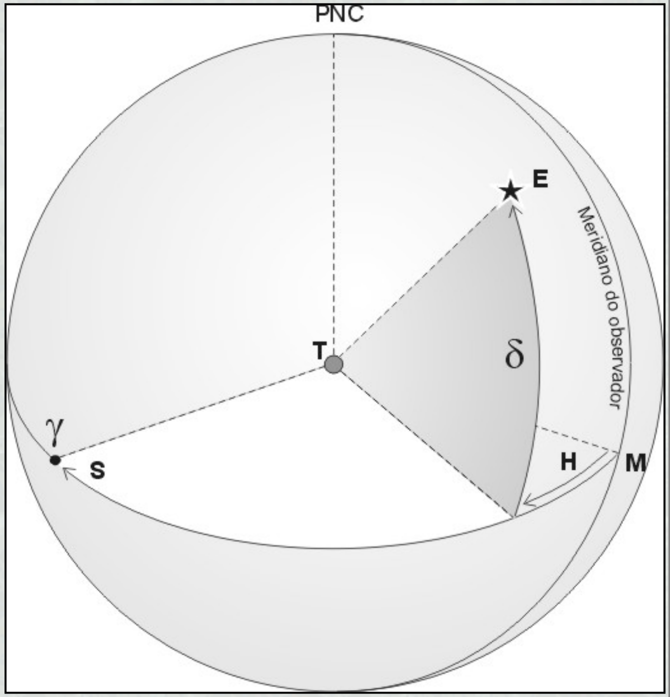

Hour angle (HA) of a celestial body

- ∡ between the observer's local meridian (which connects the zenith with the Celestial North Pole) and the RA of a celestial body.
- It indicates how far East/West the object is from the local meridian
- HA > 0: object is to the West of the meridian (already passed it)
- HA < 0: object still East of local meridian
- When observing, it is useful to consider the HA of an object to characterize its position in the local night sky.

http://www.if.ufrgs.br/oei/santiago/fis2005/textos/sistcrds.htm

Coordinate system — the celestial sphere

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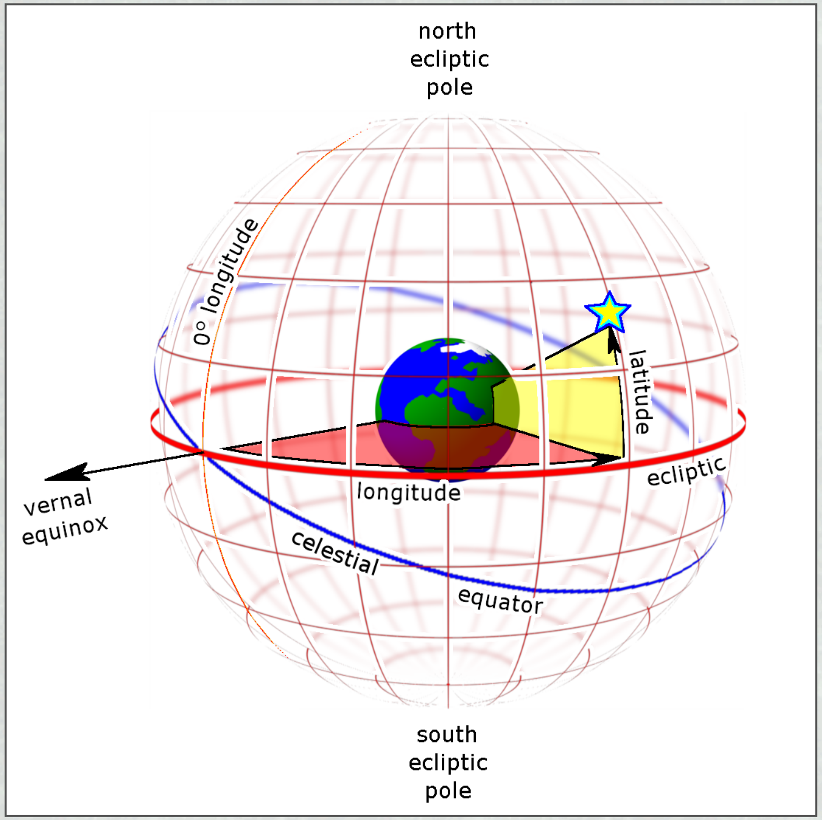
  (3) Ecliptic system: *ecliptic latitude (β) and longitude (λ)*

  - Plane of reference for latitude: ecliptic
  - Point of reference for longitude: vernal point (♈)

    —> particularly useful for Solar System objects.



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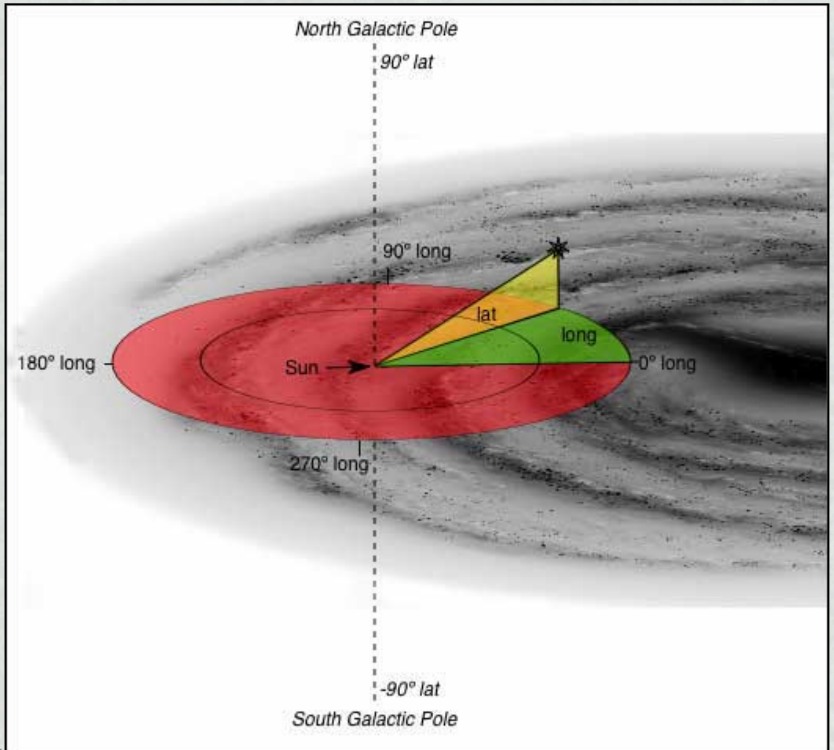
  (4) Galactic system: G*alactic latitude (b) and longitude (**l**)*

  - Plane of reference for latitude: Galactic equator
  - Point of reference for longitude: Sagittarius constellation (Milky Way center)



http://www.thinkastronomy.com/M13/Manual/common/galactic_coords.html

Coordinate system — the celestial sphere

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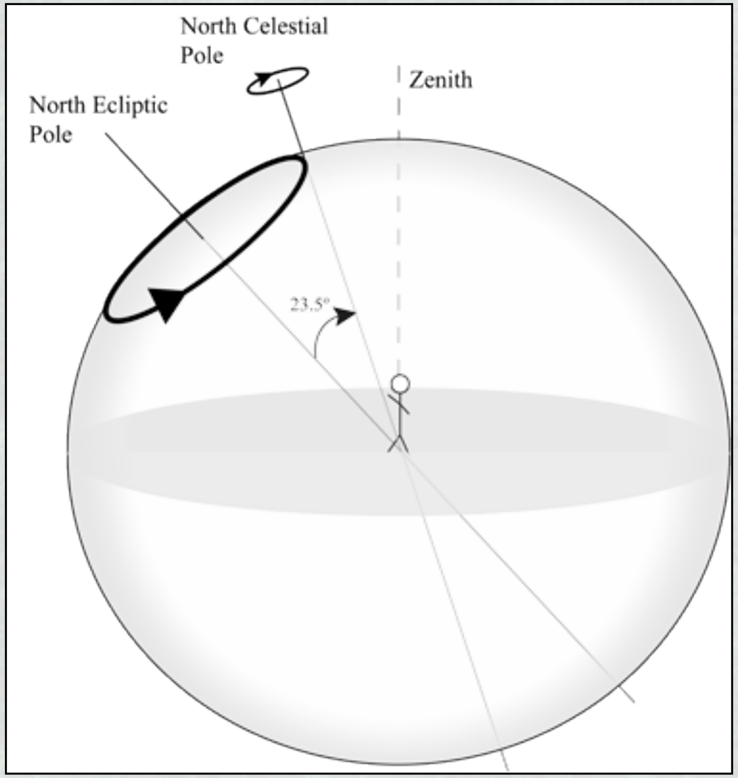
  (4) Galactic system: G*alactic latitude (b) and longitude (l)*

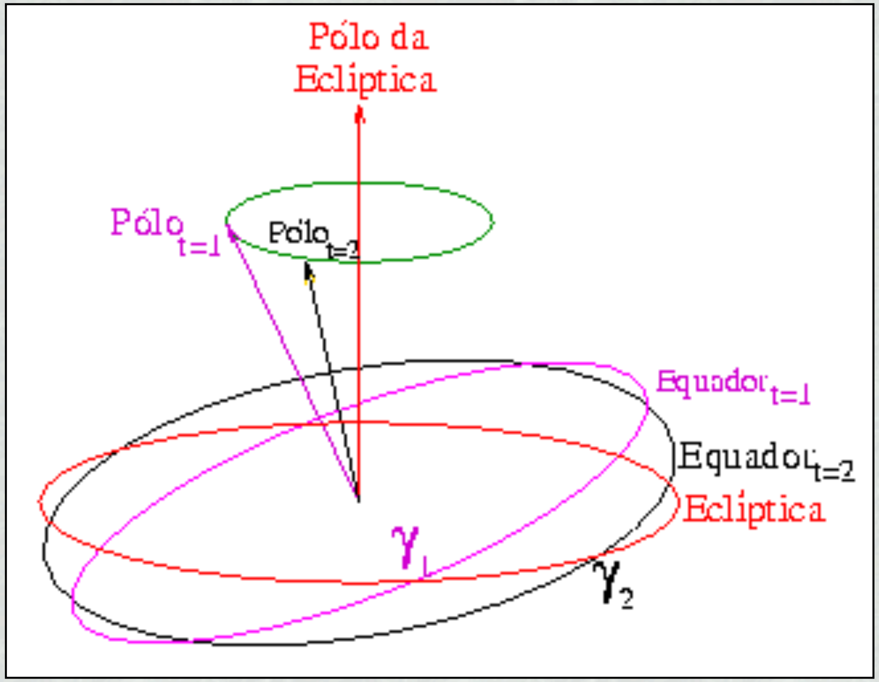
The Horizontal system depends on the observer's location.
The Equatorial system does not.

Coordinate system — precession

- As Earth revolves around the Sun, it rotates on its own axis at an angle of 23.5° from vertical (or 66.5° from the ecliptic).
- However, the Earth's rotation axis precesses around the North Pole of the Ecliptic with a period of ~26,000 years.
- Some direct consequences are shifts in:
  - Celestial Poles
  - Vernal Point



https://dept.astro.lsa.umich.edu/ugactivities/Labs/precession/index.htm



http://astro.if.ufrgs.br/fordif/node8.htm

Coordinate system — precession

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- Some direct consequences are shifts in:
  - Celestial Poles
  - Vernal Point

—> Equatorial coordinates vary with time —> An object's coordinates need to be corrected for the effect of precession.

360^o / 26000 yrs =
0.014^o/yr x 50 years
= 0.7^o!!

Coordinate system — epoch conversion

- Catalogs/Papers provide coordinates with a given **epoch** (B1950.0 or J2000.0), based on the positions of the poles and vernal point at these times (1950 or 2000)

Need to convert from one epoch to the other?

https://ned.ipac.caltech.edu/forms/calculator.html

Question:
Considering the just-calculated "ideal RA" for this epoch (2nd week of July) — which one of these objects is more likely to be accessible for a South-based telescope?

Table 1. Observed AGNs

Romero+99

Object	$\alpha_{1950.0}$	$\delta_{1950.0}$	z	m_V	Type
0537 − 441	05 37 21.1	−44 06 45.0	0.894	16.48	RBL
0637 − 752	06 37 23.25	−75 13 38.2	0.651	15.75	RLQ
1034 − 293	10 34 55.9	−29 18 27.0	0.312	16.46	RLQ
1101 − 232	11 01 11.1	−23 13 20.0	0.186	16.55	XBL
1120 − 272	11 20 34.2	−27 13 35.0	0.389	16.80	RQQ
1125 − 305	11 25 04.0	−30 28 14.0	0.673	16.30	RQQ
1127 − 145	11 27 35.6	−14 32 54.0	1.187	16.90	RLQ
1144 − 379	11 44 30.9	−37 55 31.0	1.048	16.20	RBL
1157 − 299	11 57 10.0	−29 55 10.0	0.207	16.40	RQQ
1244 − 255	12 44 06.7	−25 31 25.0	0.638	17.41	RLQ
1256 − 229	12 56 27.6	−22 54 28.0	?	17.30	RBL
1349 − 439	13 49 52.5	−43 57 55.0	?	16.37	RBL
1510 − 089	15 10 08.9	−08 54 48.0	0.360	16.54	RLQ
1519 − 273	15 19 37.3	−27 19 30.0	?	17.70	RBL
2005 − 489	20 05 46.6	−48 58 43.0	0.071	13.40	RBL
2155 − 304	21 55 58.3	−30 27 54.0	0.116	13.09	XBL
2200 − 181	22 00 27.0	−18 16 14.0	1.160	15.30	RQQ
2254 − 204	22 54 00.5	−20 27 43.0	?	16.60	RBL
2316 − 423	23 16 20.9	−42 23 14.0	0.055	16.00	XBL
2340 − 469	23 40 34.2	−46 56 42.0	1.970	16.40	RQQ
2341 − 444	23 41 08.2	−44 23 58.0	1.900	16.50	RQQ
2344 − 465	23 44 02.3	−46 29 10.0	1.890	16.40	RQQ
2347 − 437	23 47 57.5	−43 42 31.0	2.900	16.30	RQQ

Coordinate system — epoch conversion

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Need to convert from
one epoch to the other?

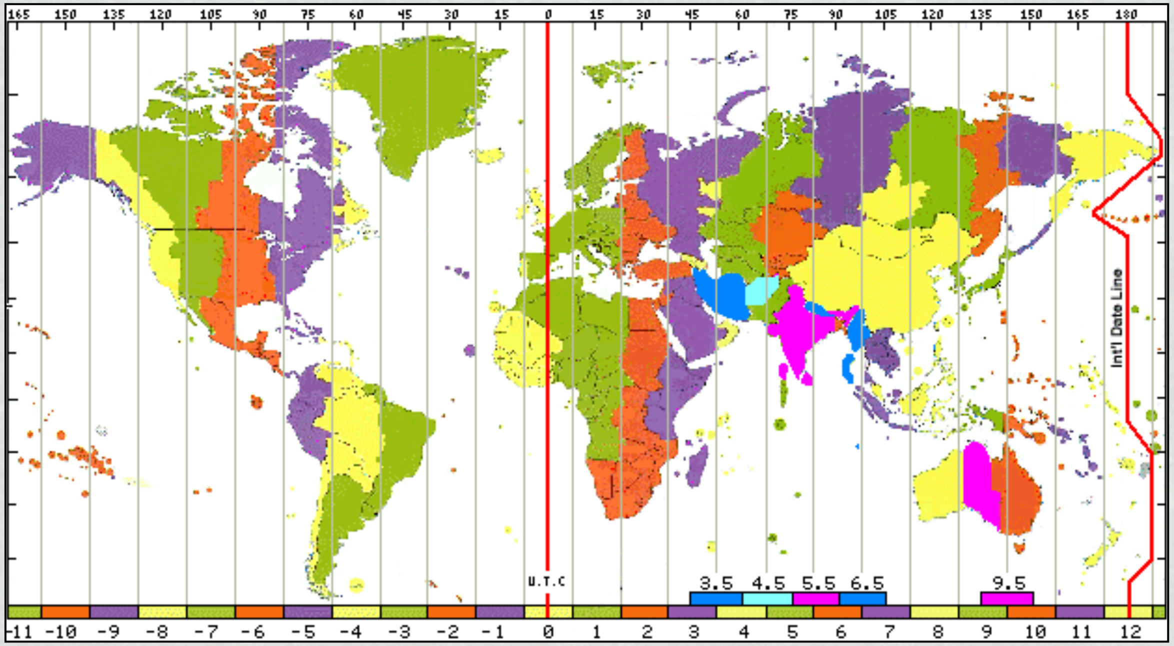
https://ned.ipac.caltech.edu/forms/calculator.html

- When observing at the telescope, an object's coordinates must always be precessed prior to pointing so that the input coordinates reflect the date/time of observation.

How we measure time

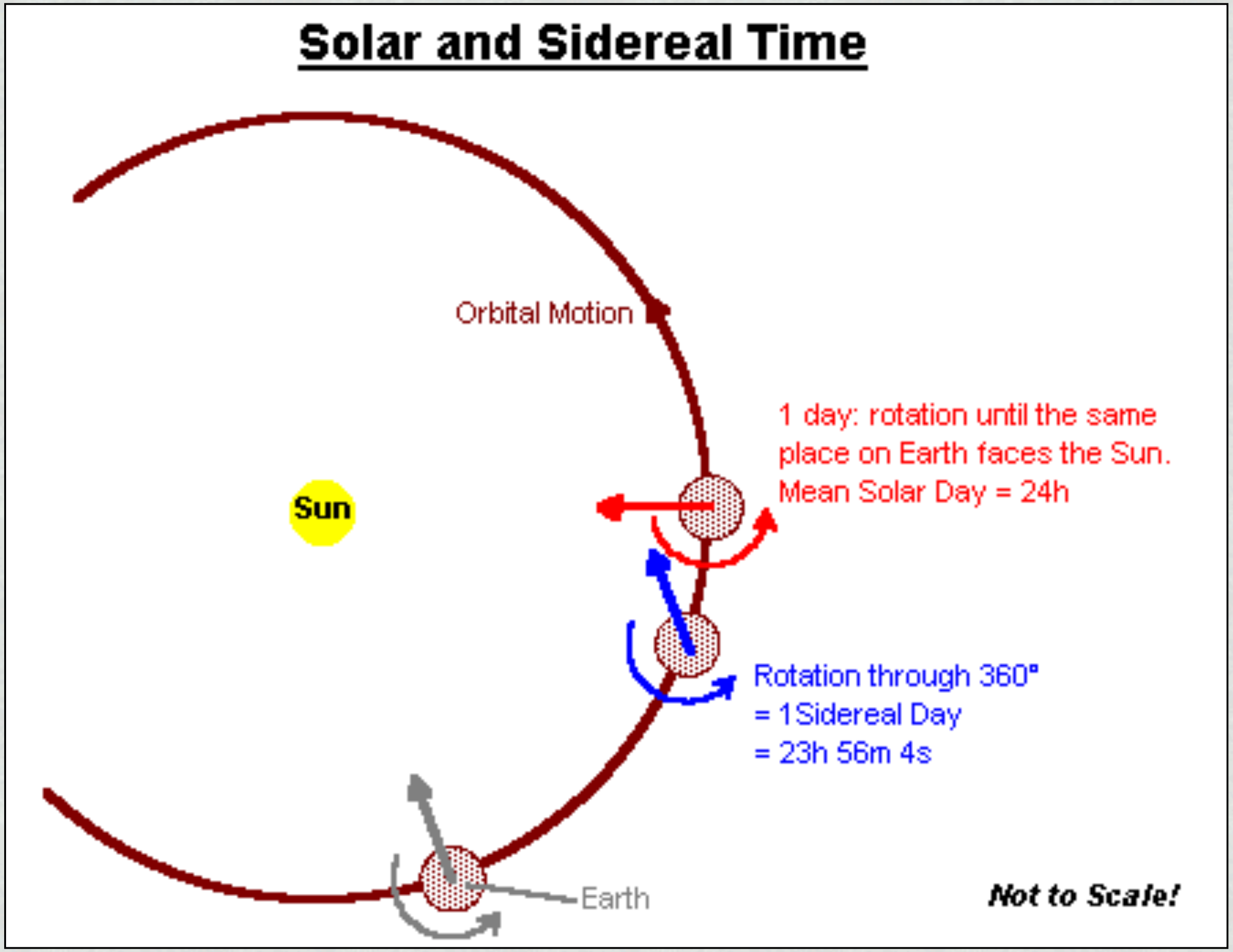
- **Local Time**
  - Based on the Sun’s position with respect to the local meridian (that connects the zenith with the celestial north pole)
  - International Meridian Conference in Washington (1884)
    - 25 countries got together an established a reference meridian (longitude 0°) → Meridiano de Greenwich

AM: “Ante” meridian
PM: “Post” meridian



How we measure time

- Local Time
- **Local Sidereal time** (LST)



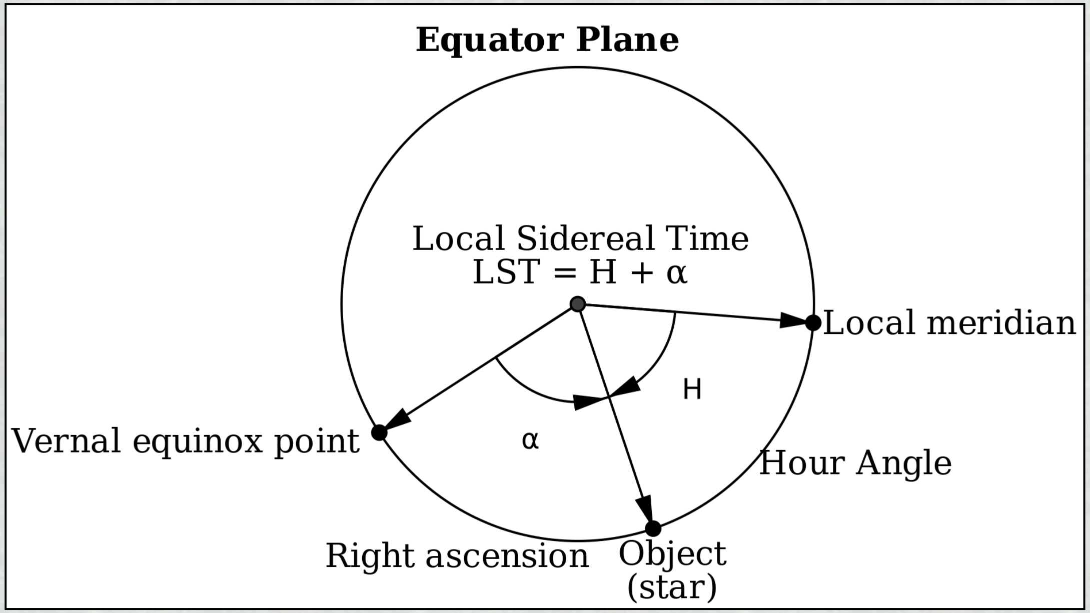
http://www.astunit.com/astunit_tutorial.php?topic=time

How we measure time

- Local Time
- **Local Sidereal time** (LST)
  - LST is based on the positions of stars: which part of the Celestial Sphere is passing through the observer's local meridian at a given time.
    - LST corresponds to the right ascension of a celestial body that is just passing through the local meridian.

- To determine the hour angle (HA) of an object, one must simply subtract its RA from the local sidereal time.

$$LST = RA_{obj} + HA_{obj}$$



Note: LST changes continuously!

http://commons.wikimedia.org/wiki/File:Local_Sidereal_Time.svg

How we measure time

- Local Time
- Local Sidereal time (LST)
- **Universal Time** (UT)
  - A time that serves as a reference for all observers on Earth.
  - Approximately equivalent to local time in Greenwich, UK (GMT = *Greenwhich Mean Time*)

$$UT = HA_{\text{Sun in Greenwich}} +/- 12^h$$

(so that midnight in Greenwich corresponds to $UT=0^h$)

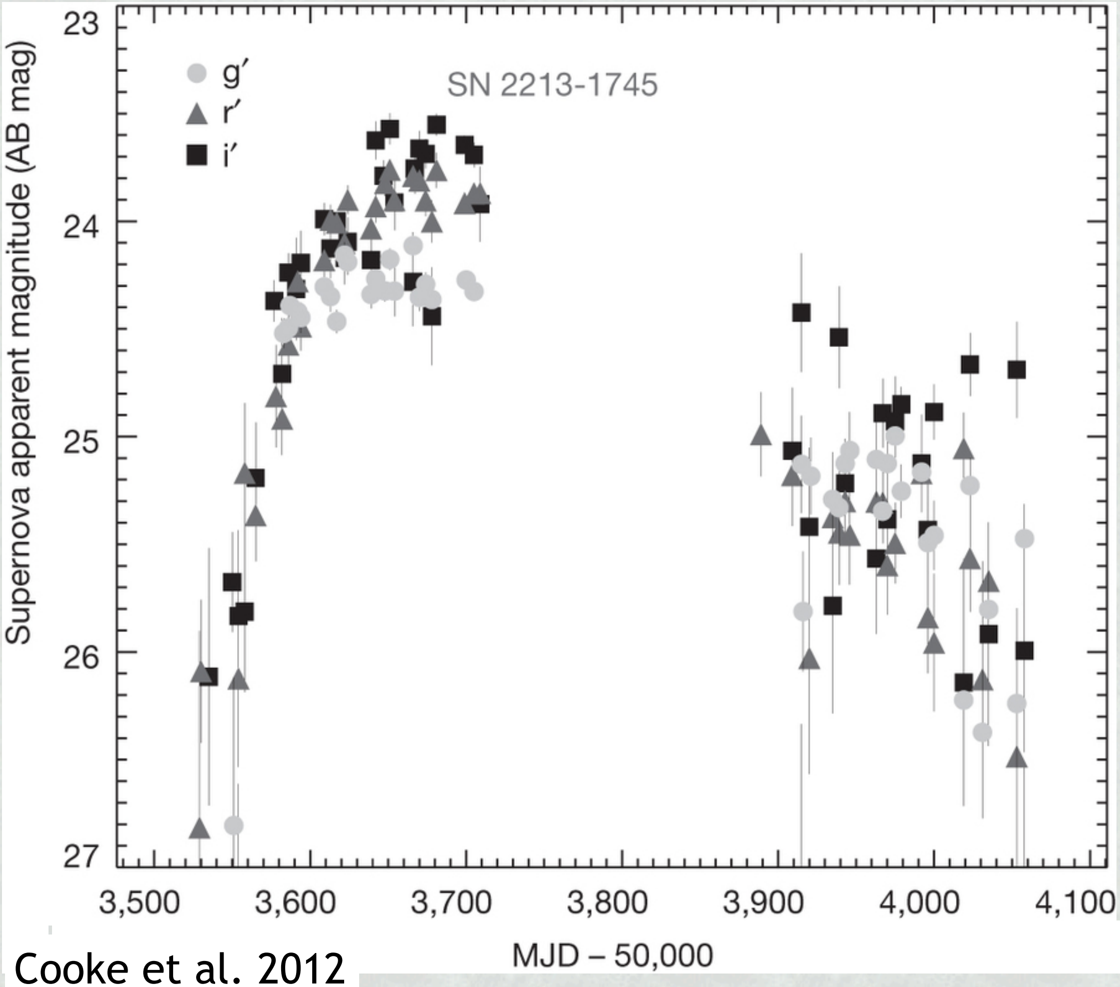
How we measure time

- Local Time
- Local Sidereal time (LST)
- Universal Time (UT)
- **Julian Date (JD)**
  - A system that counts time in units of days exclusively
    - Bypass the graphically-complex system of day/month/year/leap year, etc.
  - Day 0: January 1, 4713 BC
  - *Modified Julian Date* (MJD) = JD – 2.400.000,5
    - → Days since 17-nov-1858

How we measure time

- Local Time
- Local Sidereal time (LST)
- Universal Time (UT)
- **Julian Date (JD)**

– Convenient in the context of transient events (e.g., supernovae), planet transit, stellar variability, etc.



Cooke et al. 2012

How we measure time

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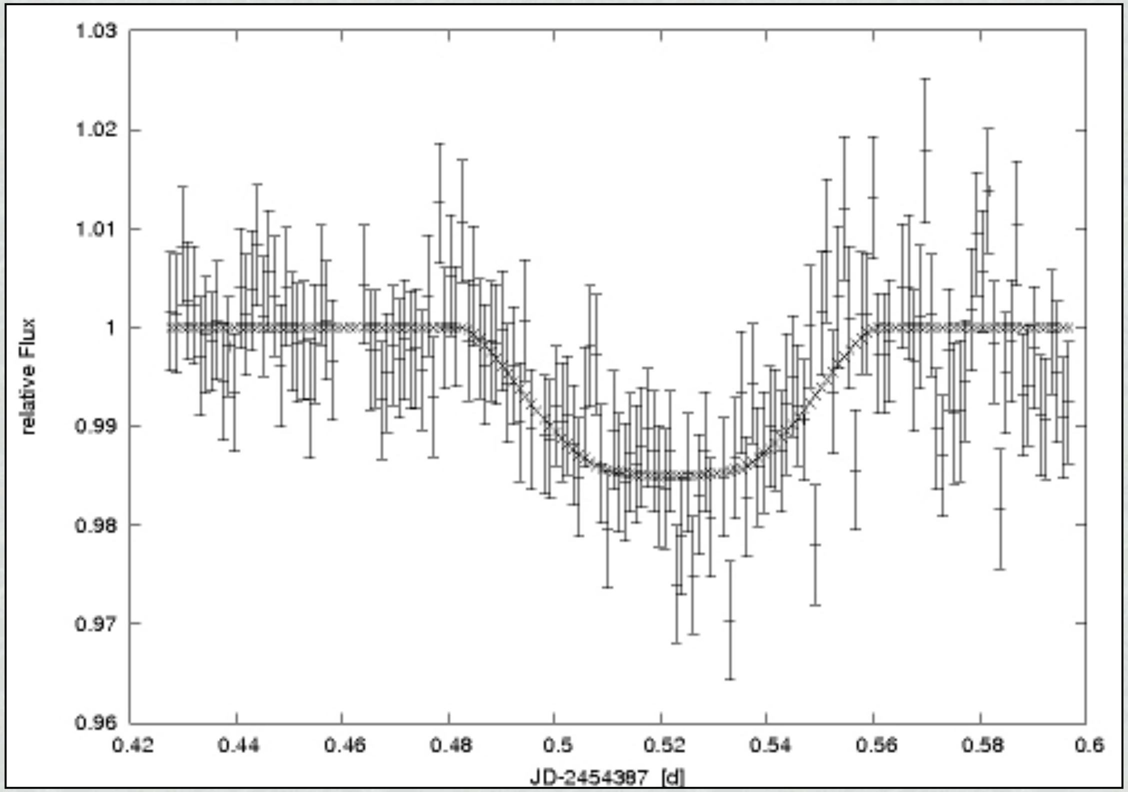
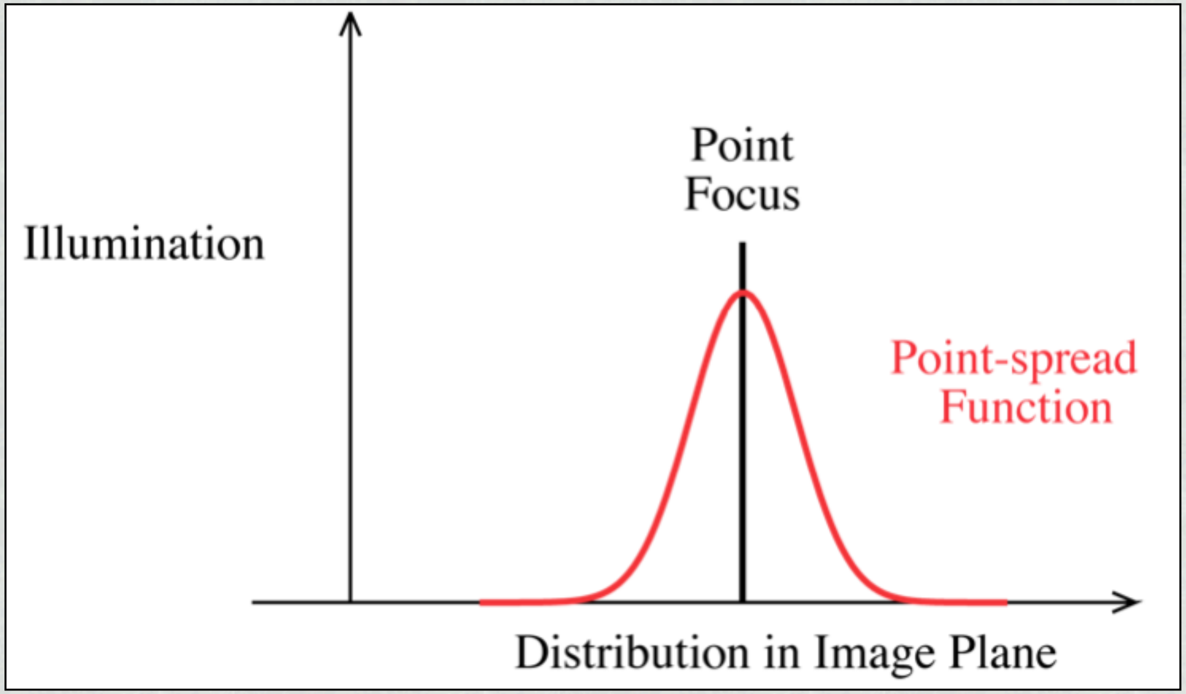


http://www.astro.uni-jena.de/oldstuff/AN/art13.html

Image Quality: the Point-Spread Function (PSF)

- Ideally, a telescope focusses parallel light rays onto a perfect point.
- In reality, the resulting image is “blurred out” around this ideal focussed point —> this dispersion is characterized by the PSF.
- The PSF describes the angular resolution of a telescope.



http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/aber2.html

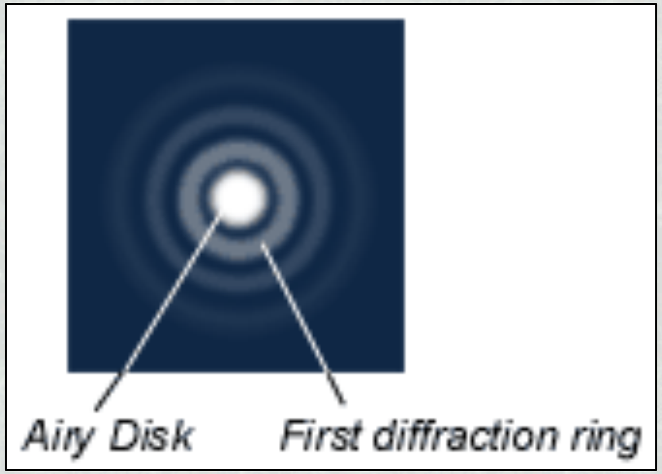
Image Quality: the Point-Spread Function (PSF)

- Many effects contribute to the PSF of an instrument:
  - Limit of diffraction (given by the Rayleigh criterion)
  - Atmospheric turbulence (seeing)
  - Aberrations due to the collection of lenses/mirrors used
    - These can be minimized

Image Quality: Diffraction limit

- **Diffraction** occurs when light encounters obstacles along its path.
- In telescopes — which are composed of a large metallic structure that holds a finite, round aperture, a secondary mirror, etc. — light interacts with walls and edges in the structure.
- Although stars are ideally point sources (due to their large distances), even in the best conditions the resulting image is that of a diffraction pattern: a disk of finite size (Airy disk) and diffraction rings of lower brightness.

~84% of the energy is within the central source in the diffraction pattern



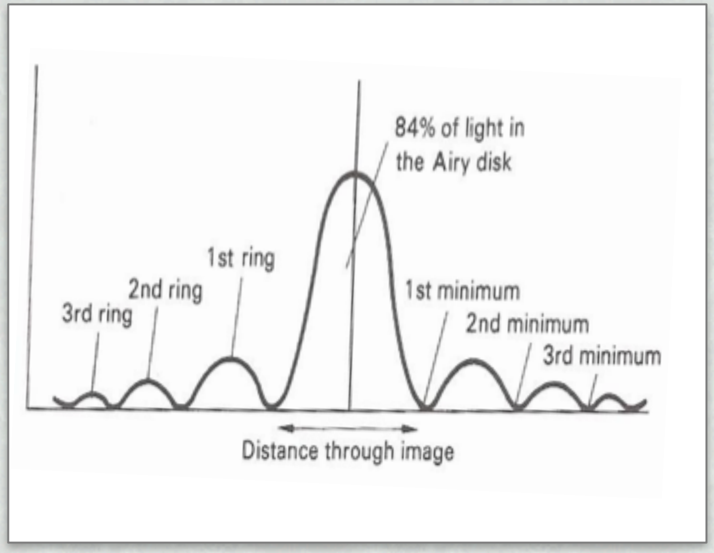


Image Quality: Rayleigh Criterion

- Two objects are considered to be spatially resolved (i.e., distinguishable from each other) if the distance between the diffraction pattern maxima is larger than the distance to the first minimum.

- Rayleigh Criterion:
  - The first minimum is a distance d_0 from the center of the Airy Disk:

$$d_0 = 1.22\ \lambda/D$$

$$\sim \lambda/D$$

where:

D = telescope's aperture

D, λ [same units]

d_0 = angular resolution

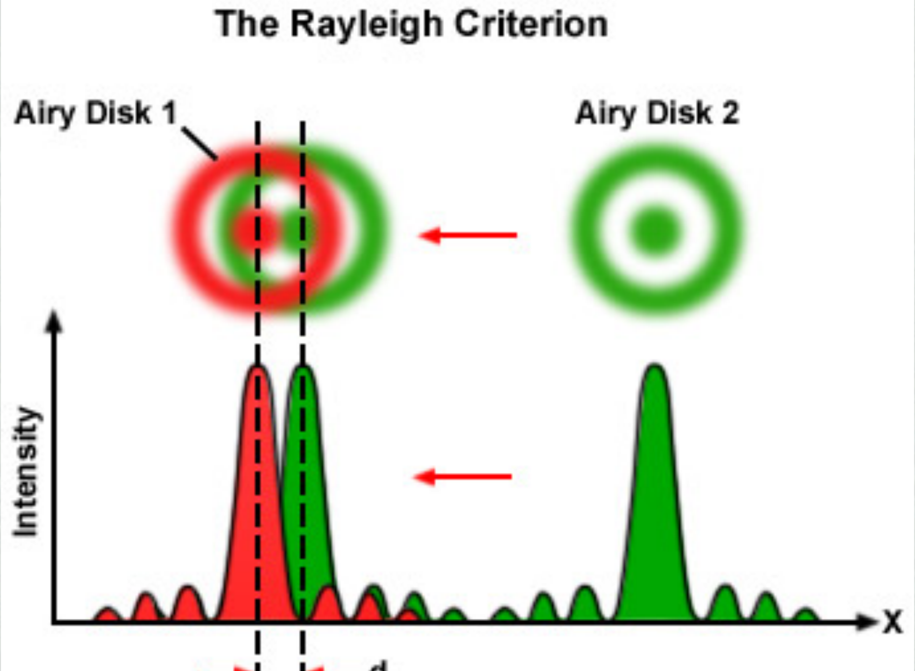


Figure 4

http://zeiss-campus.magnet.fsu.edu/articles/basics/resolution.html

Image Quality: Rayleigh Criterion

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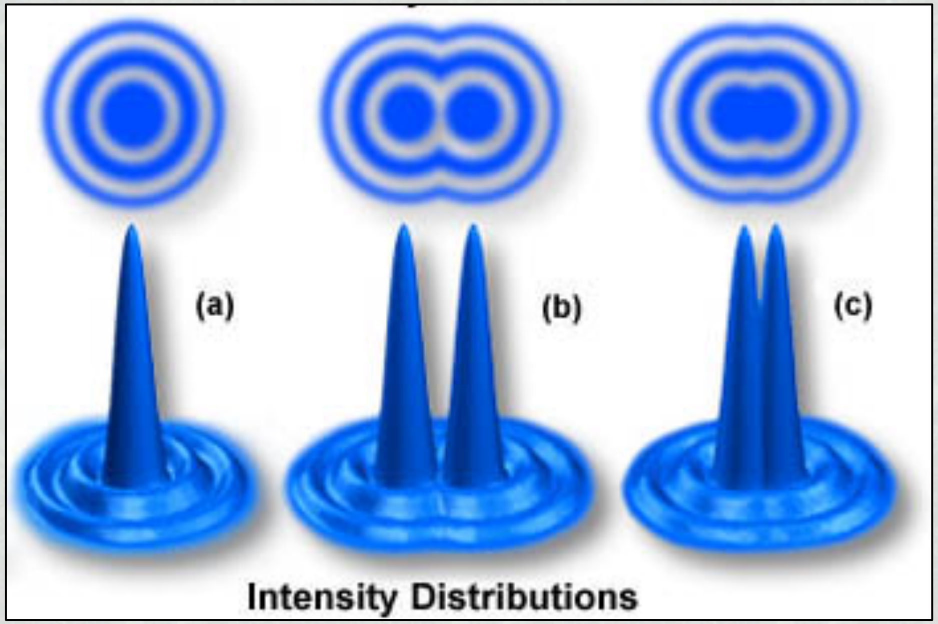


(a) Single-object diffraction pattern
(b) Two diffraction patterns
→ objects are resolved
(c) Objects are NOT resolved

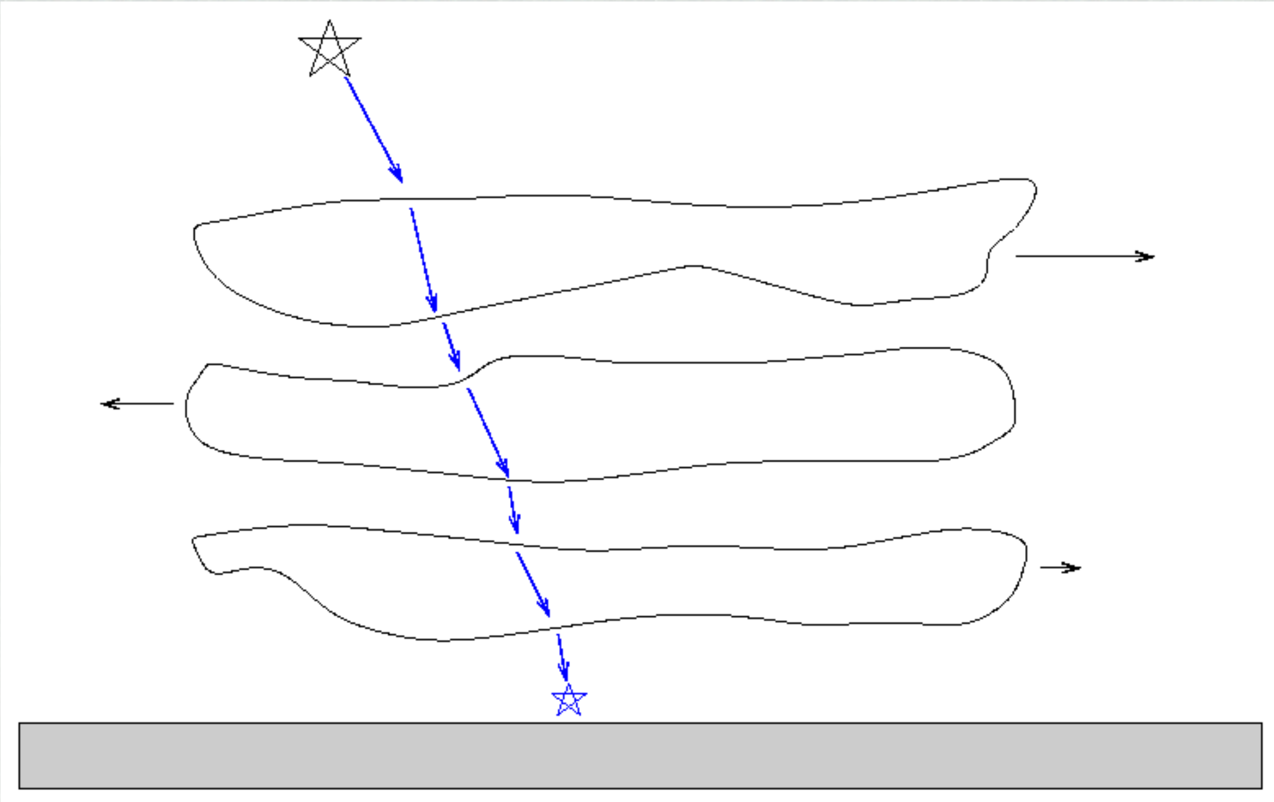
http://micro.magnet.fsu.edu/primer/anatomy/numaperture.html

Image Quality: the Point-Spread Function (PSF)

- Many effects contribute to the PSF of an instrument:
  - Limit of diffraction —> ~λ/D
    - dominates the PSF at larger λ (e.g., radio)
      - as we'll see, the impact of atmospheric turbulence is insignificant at these wavebands
      - Example: HI (21cm) observations with Arecibo (D~300m)
        - Limit of diffraction: ~ 0.0007 radians ~ 2 arcmins
  - Atmospheric Turbulence (*seeing*)
    - In optical/near-IR observations taken with ground-based telescopes, biggest contributor to PSF size —> limits the angular resolution of images
    - Typical (good) seeing ~1"

Image Quality: *seeing*

- Turbulence in atmosphere causes small-scale temperature and density inhomogeneities —> refraction index varies along the light rays' trajectory —> random changes in the light ray direction (timescales ~10ms)



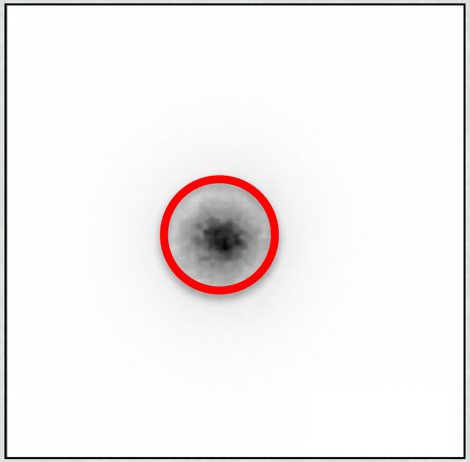
The apparent position of the celestial body changes in small timescales

→ Stars twinkle!

http://spiff.rit.edu/classes/phys445/lectures/atmos/atmos.html

Image Quality: *seeing*

Short images
(apparent position changes!)



As time goes by → sum of the apparent positions form a disk

- The multiple images of the star "dance" within the FOV
- The source spreads into an apparent disk ("seeing disk")

What about planets? Do they twinkle?

Apparent size of planets is larger than that of stars → small changes in the apparent position go undetected

→ **Planetas do not twinkle!**

Image Quality: *seeing*

Short images
(apparent position changes!)

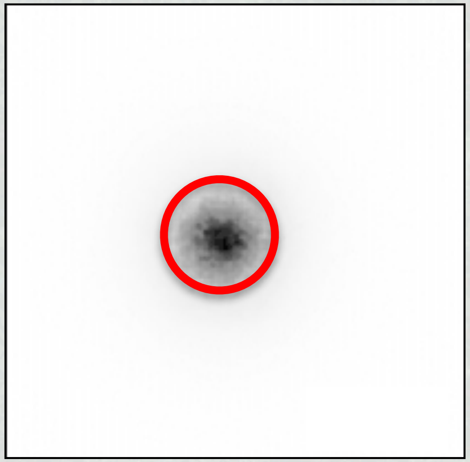


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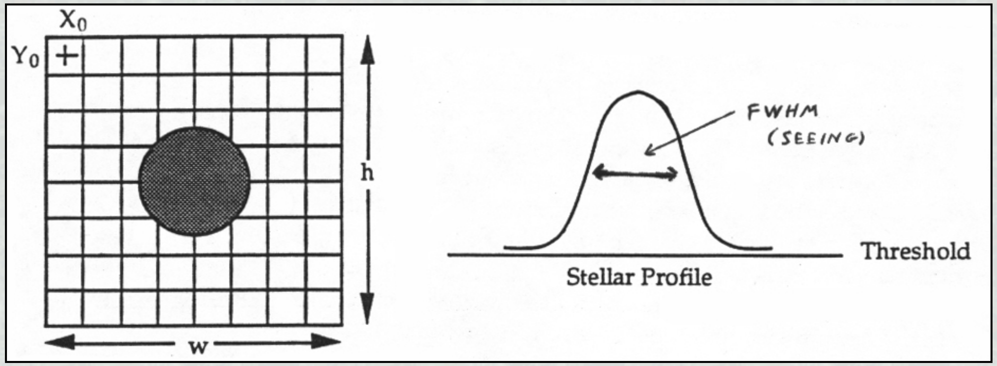
Image Quality: *seeing*

Short images
(apparent position changes!)

- The multiple images of the star "dance" within the FOV
- The source spreads into an apparent disk ("seeing disk")

- Distribution of light within this disk is well fit by a gaussian curve:



$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma^2)}$$

$$FWHM = 2.355\sigma$$

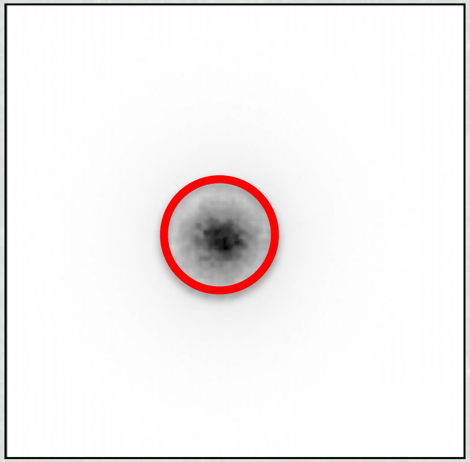


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Image Quality: *seeing*

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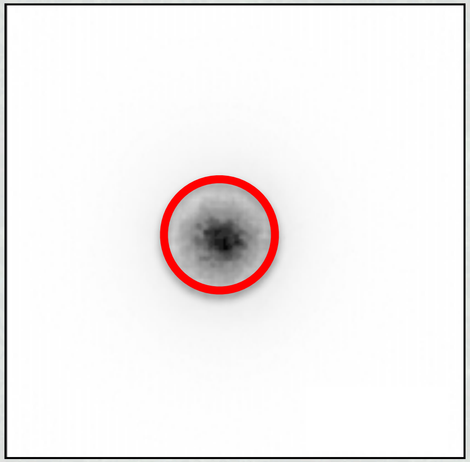
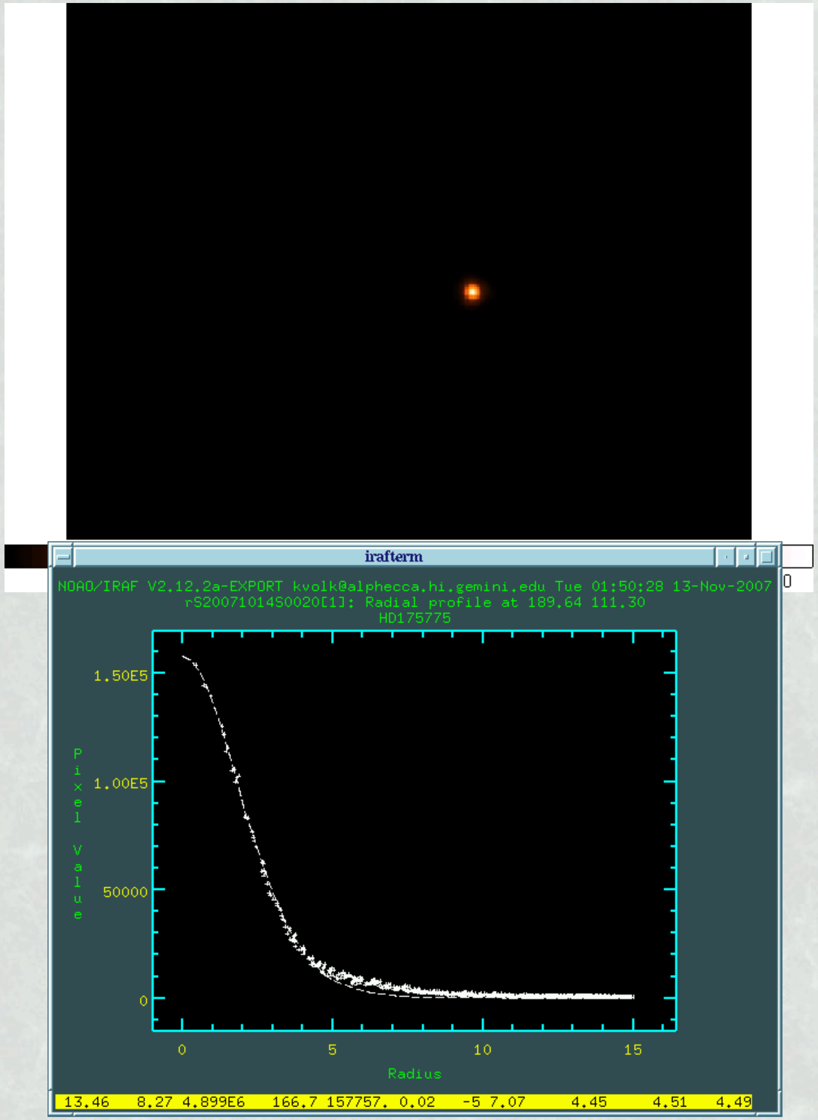


As time goes by → sum of the apparent positions form a disk

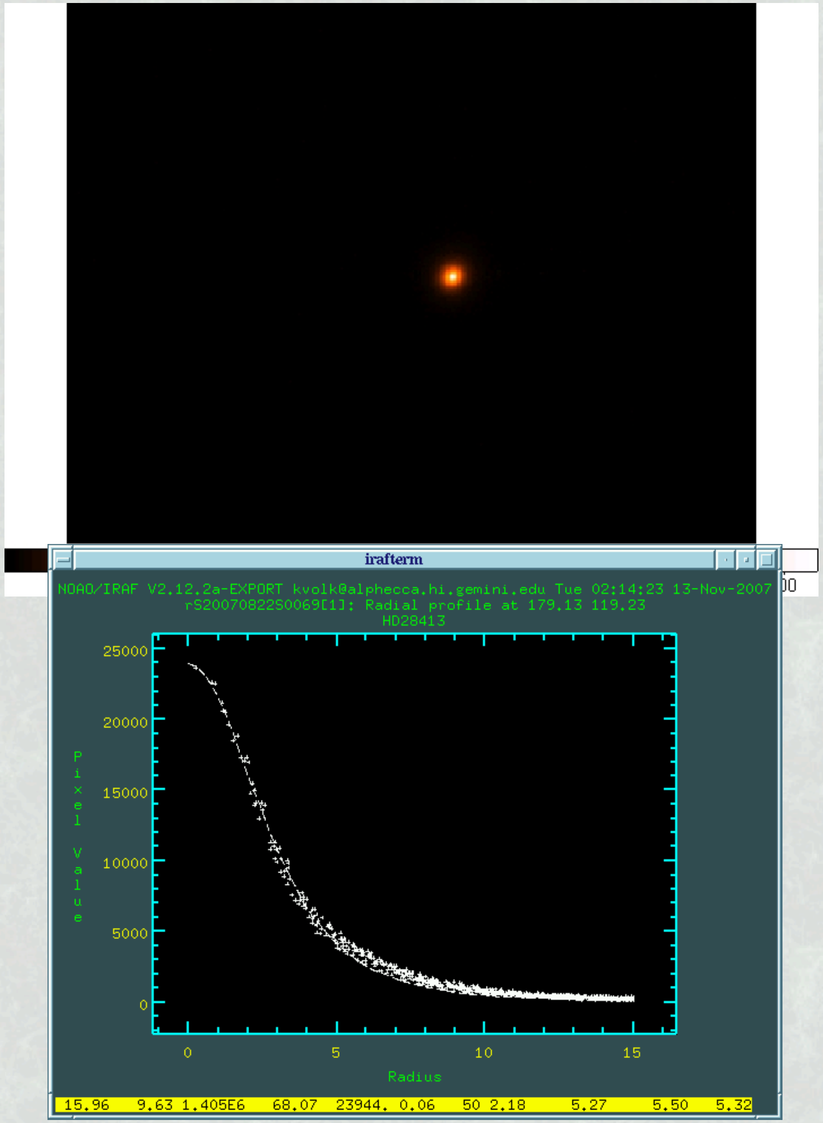
- We quantify the seeing using the size of the FWHM of the gaussian fit to the PSF
  - FWHM = seeing
  - “good seeing” → small FWHM (<1”)
  - “bad seeing” → large FWHM(>1”)

Image Quality: *seeing*

Better seeing



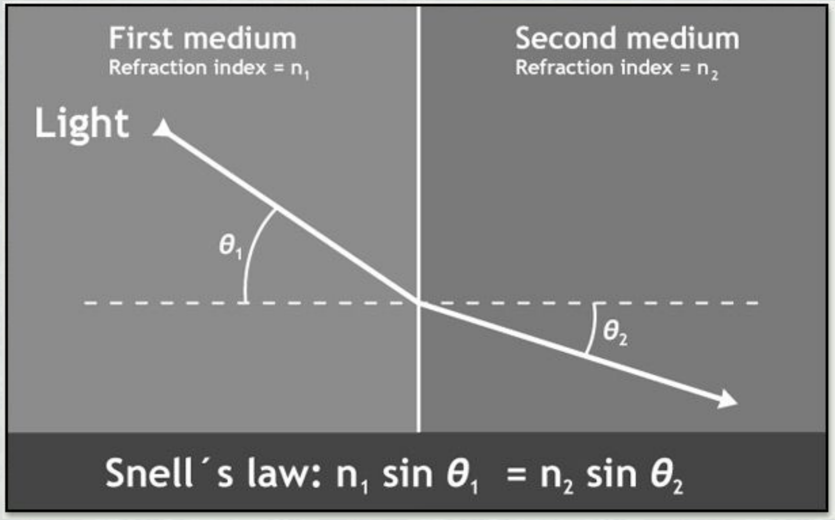
Worse seeing



http://www.gemini.edu/?q=node/10582

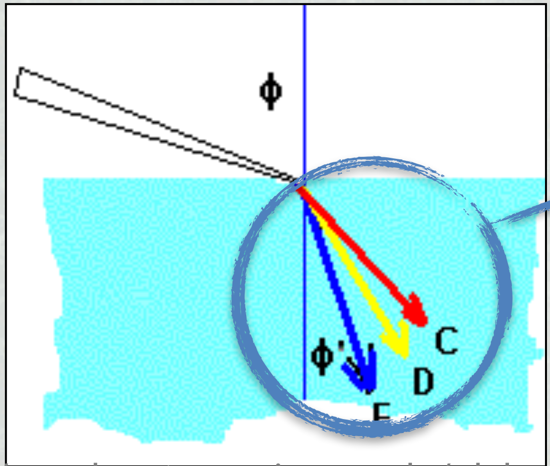
Seeing: wavelength (λ) dependence

- Snell's law:



Light deflection (θ) depends on the index of refraction

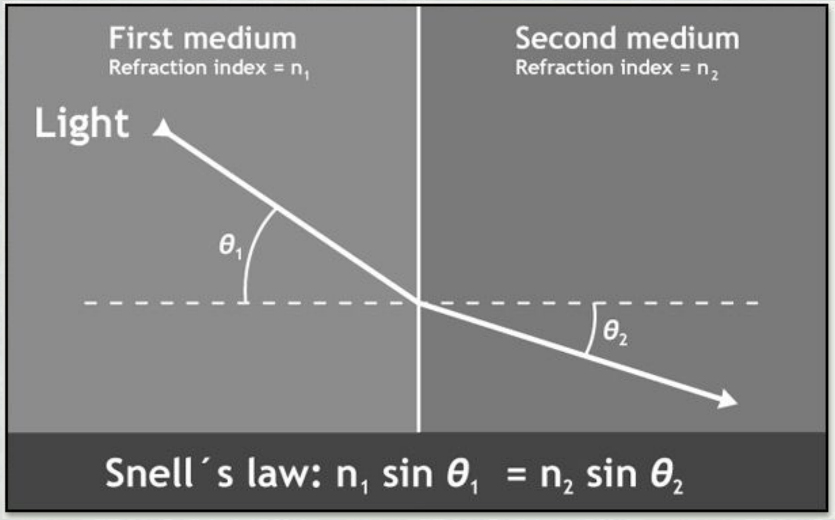
- A material's index of refraction varies with λ → **dispersion**



http://exoplanet.as.arizona.edu/~lclose/a302/lecture14/lecture_14.html

Seeing: wavelength (λ) dependence

- Snell's law:



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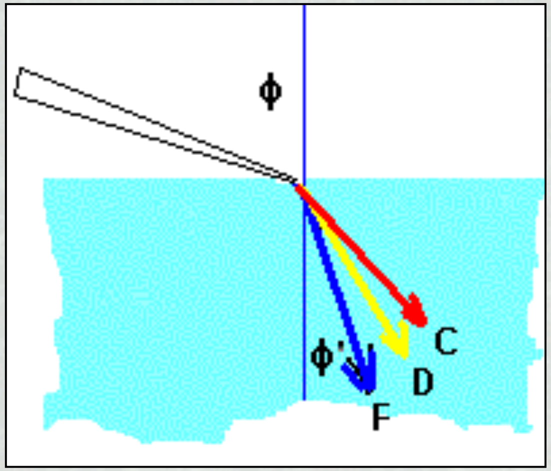
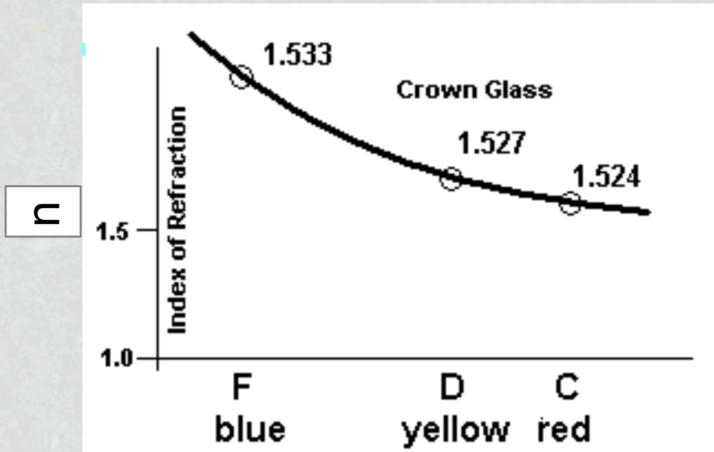




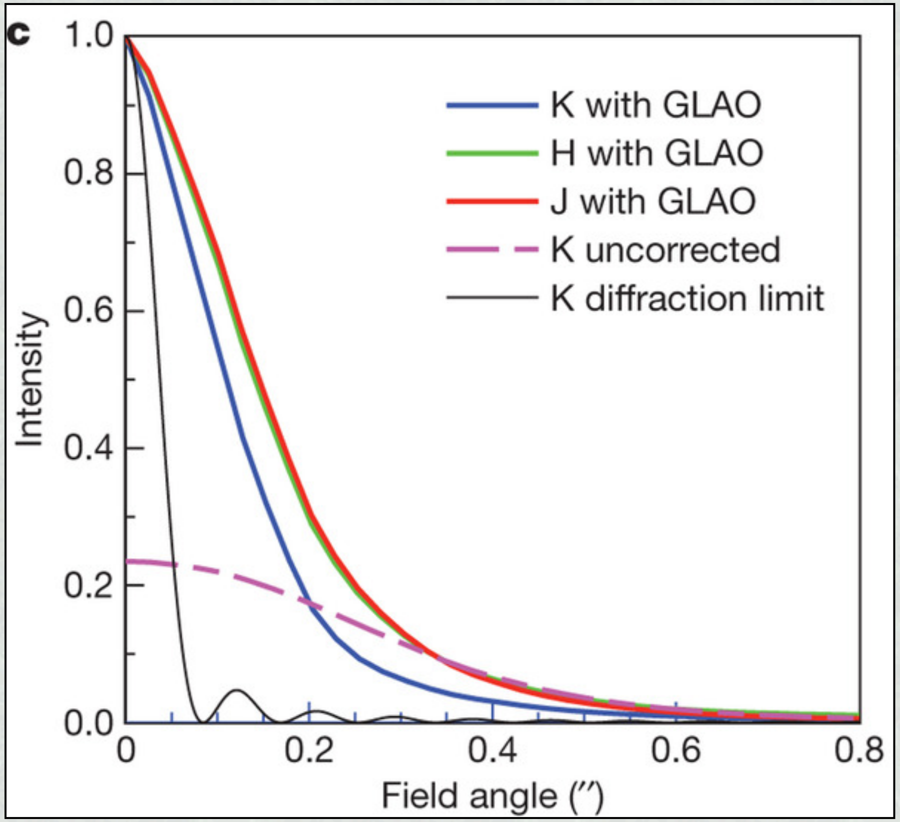
n decreases with increasing λ

Which λ is more affected?

http://exoplanet.as.arizona.edu/~lclose/a302/lecture14/lecture_14.html

Seeing: wavelength (λ) dependence

- The disk extension due to seeing is smaller in redder bands —> bluer bands are more affected by seeing (i.e., for the same atmospheric conditions, the resulting PSF is larger)



Hart et al. 2010, Nature
MMT, Arizona (EUA)

PSF and seeing

- The angular resolution of ground-based telescopes is limited by the seeing.

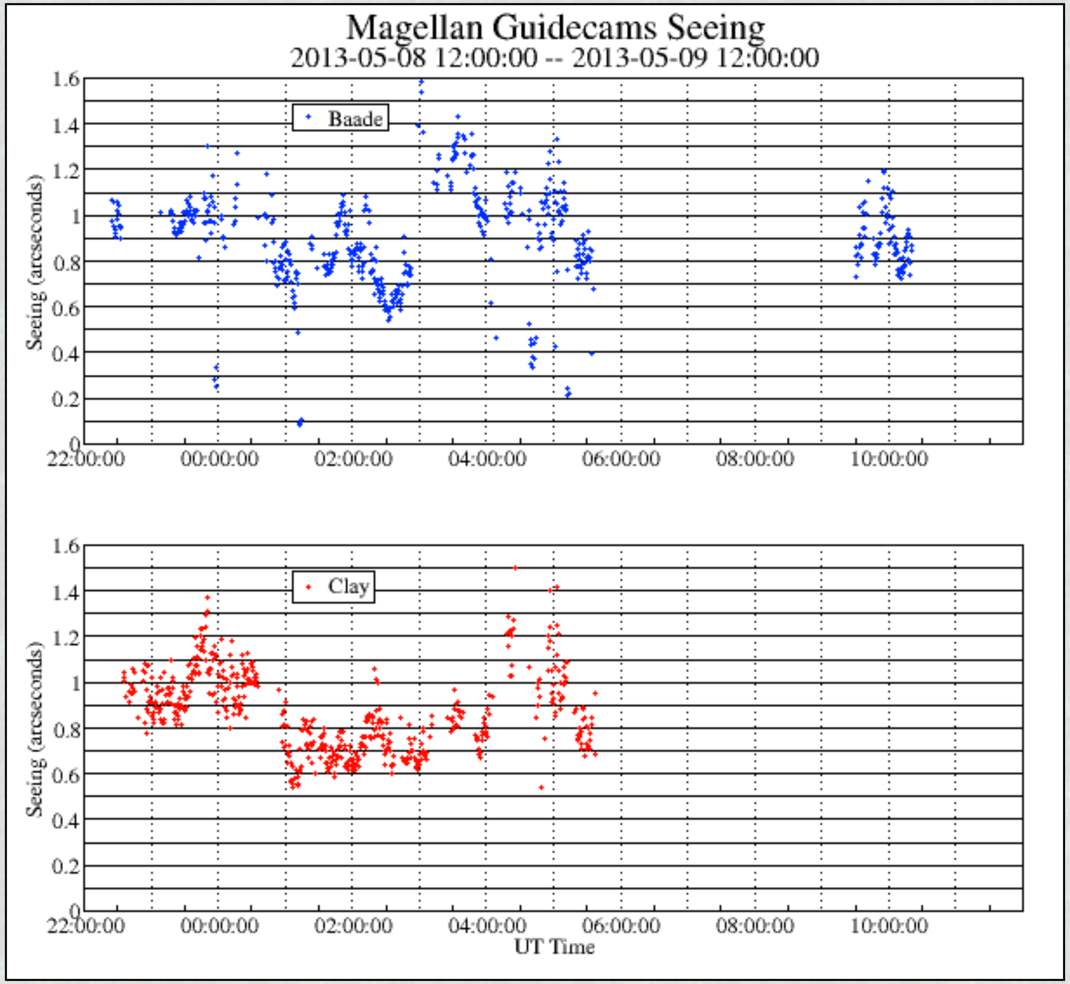
Magellan Telescopes guidecam Seeing

Local Time Date 2013 May 8

Submit

Corrigido pela massa de ar:

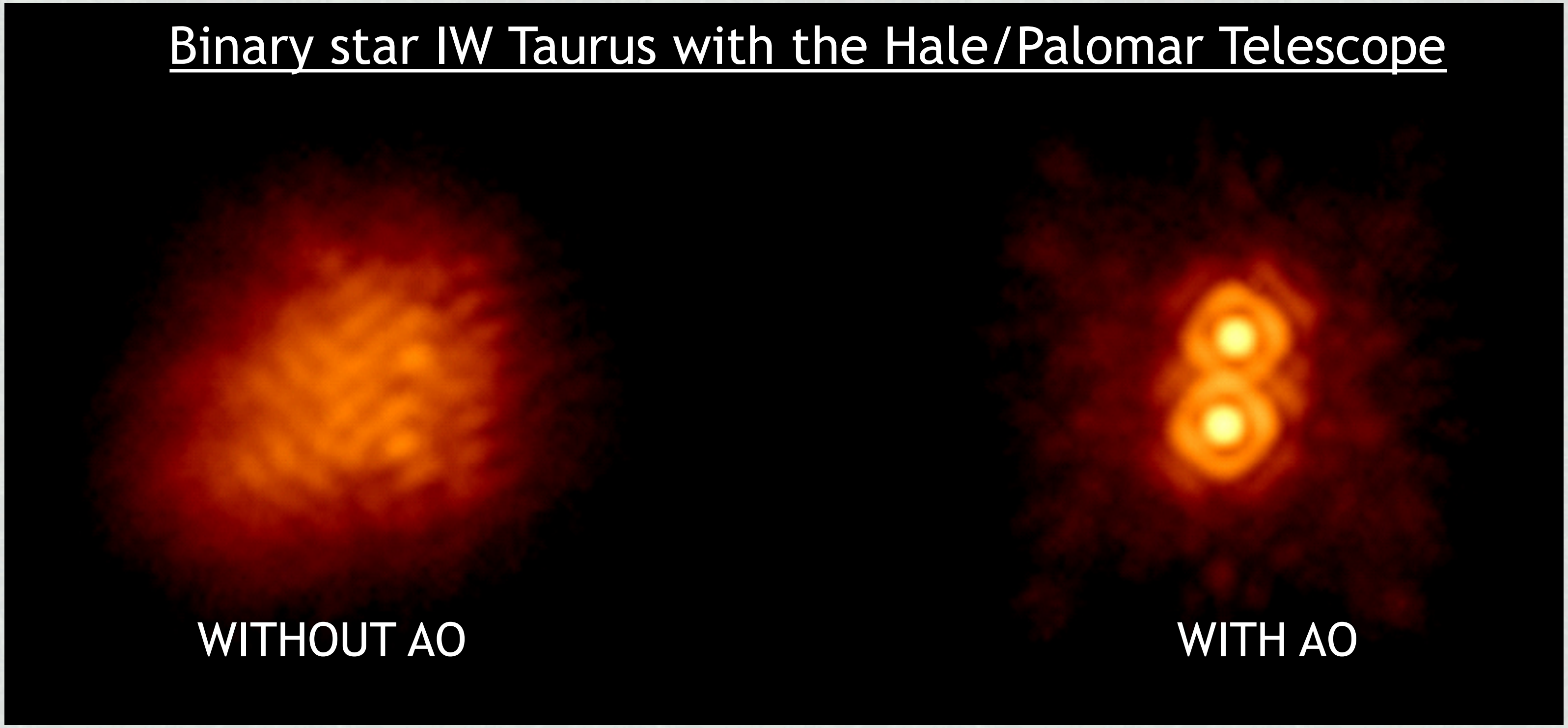
$FWHM_{corr} = FWHM_{obs} / airmass^{0.6}$



What about space-based telescopes?

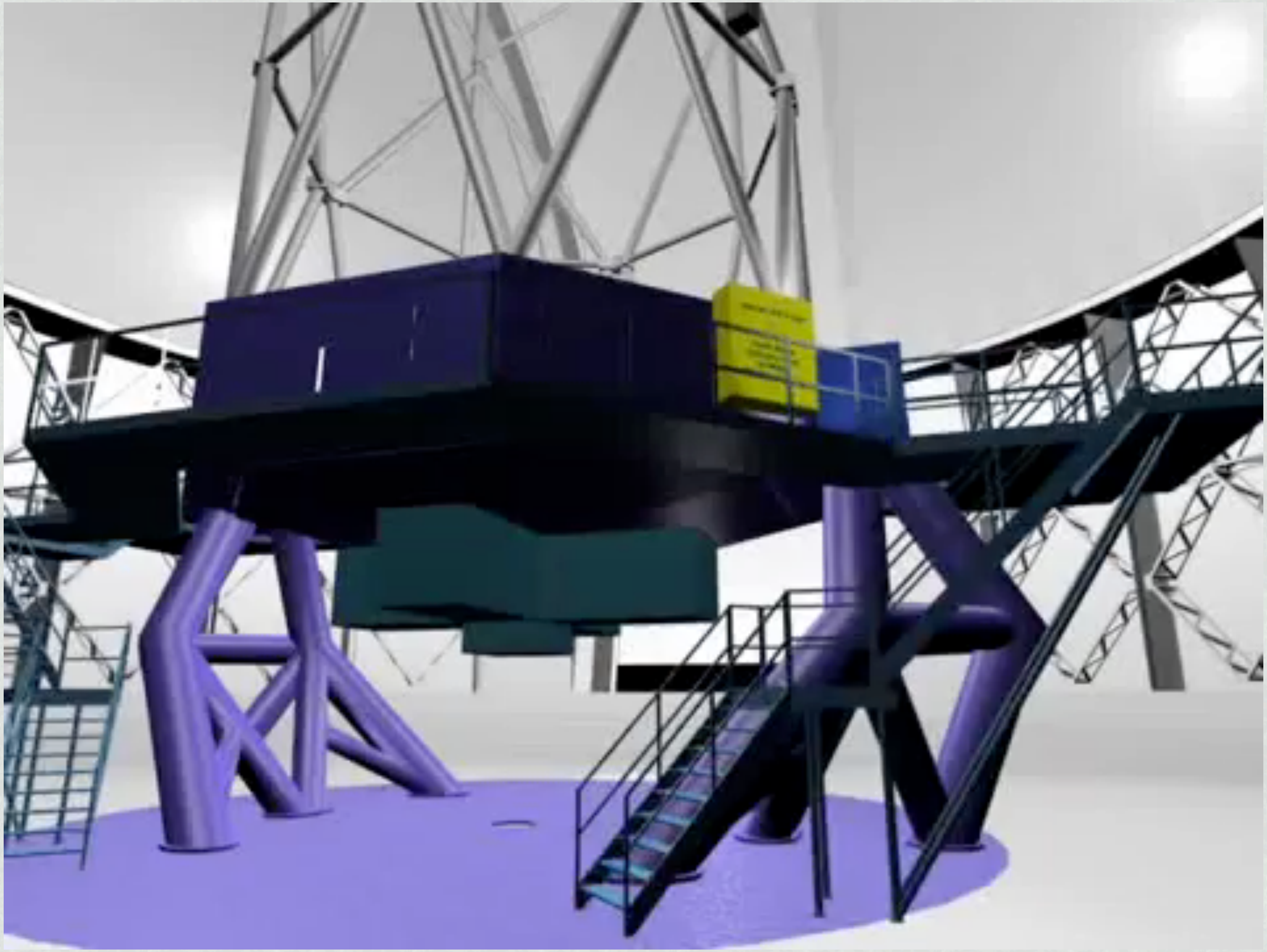
Beating down atmospheric effects from the ground

- Adaptive Optics (AO) — a technique based on the use of deformable mirrors to correct for distortions that atmosphere produces in observed image
  - Improves angular resolution down to the diffraction limit



http://www.astro.caltech.edu/palomar/AO/

Adaptive Optics (AO)
— beating down atmospheric effects from the ground



https://www.youtube.com/watch?v=3BpT_tXYy_I