AY 20 Fall 2010

Basic Optics, Telescopes, Celestial Sphere

Reading: Carroll & Ostley, Chapters 6 and 1

Resolution

Chapter 3 The Continuous Spectrum of Light

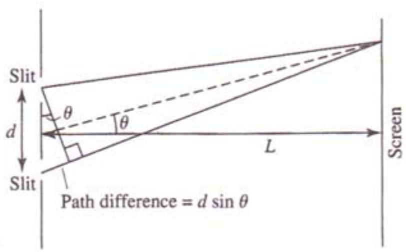


FIGURE 3.3 Double-slit experiment.

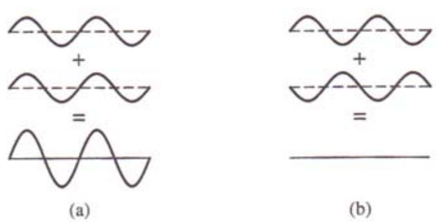


FIGURE 3.4 Superposition principle for light waves. (a) Constructive interference. (b) Destructiv
interference

Young's double slit experiment demonstrates interference effects on light "waves"

waves in phase amplify
waves out of phase cancel
See C & O §3.3

Resolution - ability to separate 2 sources that are close on sky

Limited by:

- focal length
- diffraction patterns of sources

Young's double slit experiment:

monochromatic light (λ)from single source, passes through 2 slits, distance, d, apart

path length to screen from slits differs by ~ dsinθ (L >> d)

constructive interference:

$d\sin\theta = n\lambda$ (in phase)

($d\sin\theta = 0, \lambda, 2\lambda, 3\lambda$...)

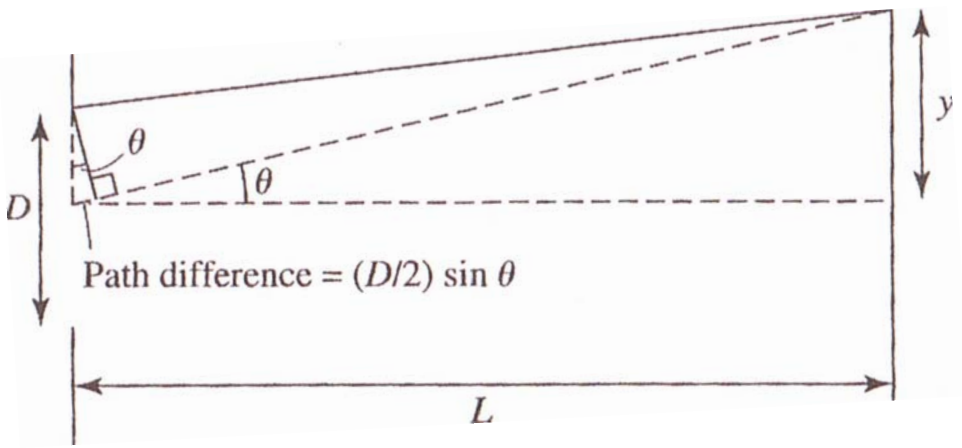
destructive interference:

$d\sin\theta = (n - \frac{1}{2})\lambda$ (out of phase)

($d\sin\theta = \frac{1}{2}\lambda, 3/2\lambda, 5/2\lambda$...)

→diffraction pattern

Advancing wavefronts of light from adjacent sources ≡ single slit diffraction pattern



Single slit experiment;
2 rays separated by D/2 converge at same point in focal plane
(every ray associated with another at separation D/2)

Path difference for rays = $(D/2)\sin\theta$

For destructive interference with n=1, path difference = $\lambda/2$

∴ condition for destructive interference here is:

$(D/2)\sin\theta = \lambda/2$, or $\sin\theta = \lambda/D$

Can consider D as 4 segments:
ray at slit edge paired with another at distance D/4 away

∴ destructive interference if

$(D/4)\sin\theta = \lambda/2$, or $\sin\theta = 2\lambda/D$

etc etc for 6, 8, 10…segments

∴ condition for light minima

$\sin\theta = m\lambda/D$, m an integer

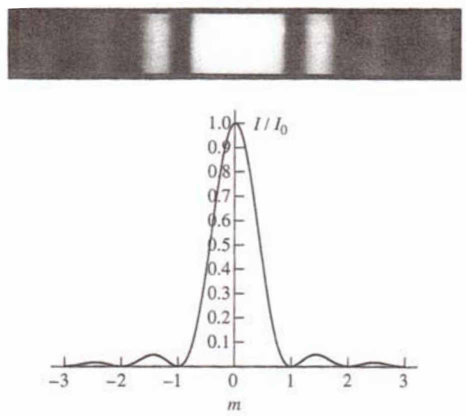


FIGURE 6.8 The diffraction pattern produced by a single slit. (Photograph from Cagnet, Francon and Thrierr, *Atlas of Optical Phenomena*, Springer-Verlag, Berlin, 1962.)

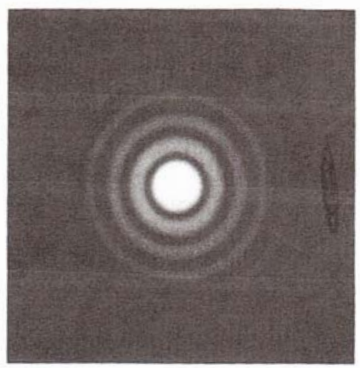


FIGURE 6.9 The circular aperture diffraction pattern of a point source. (Photograph from Cagnet, Francon, and Thrierr, *Atlas of Optical Phenomena*, Springer-Verlag, Berlin, 1962.)

Diffraction pattern for point source and telescope from circular aperture solution (not slit)

$\sin\theta = m\lambda/D$ applies

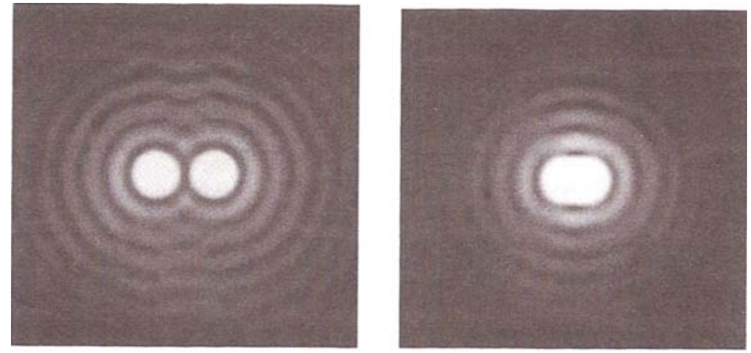
but m is not loneger an integral

Central maximum (m = 0)

= Airy disk

Ring	m
Central maximum	0.000
First minimum	1.220
Second maximum	1.356
Second minimum	2.333
Third maximum	2.679
Third minimum	3.238

Resolution and Airy rings


(a) (b)

For 2 sources at small angular separation, Airy rings may overlap

Resulting image is unresolved if:

central maximum of one source falls within first minimum of other

What is the minimum separation that can be resolved?

Let angular separation of sources = θ_{min}

Since θ_{min} very small, $\sin\theta_{min} \approx \theta_{min}$(radians) = $m\lambda/D$

$\therefore \; \theta_{min} = 1.22\,\lambda/D$

Rayleigh Criterion

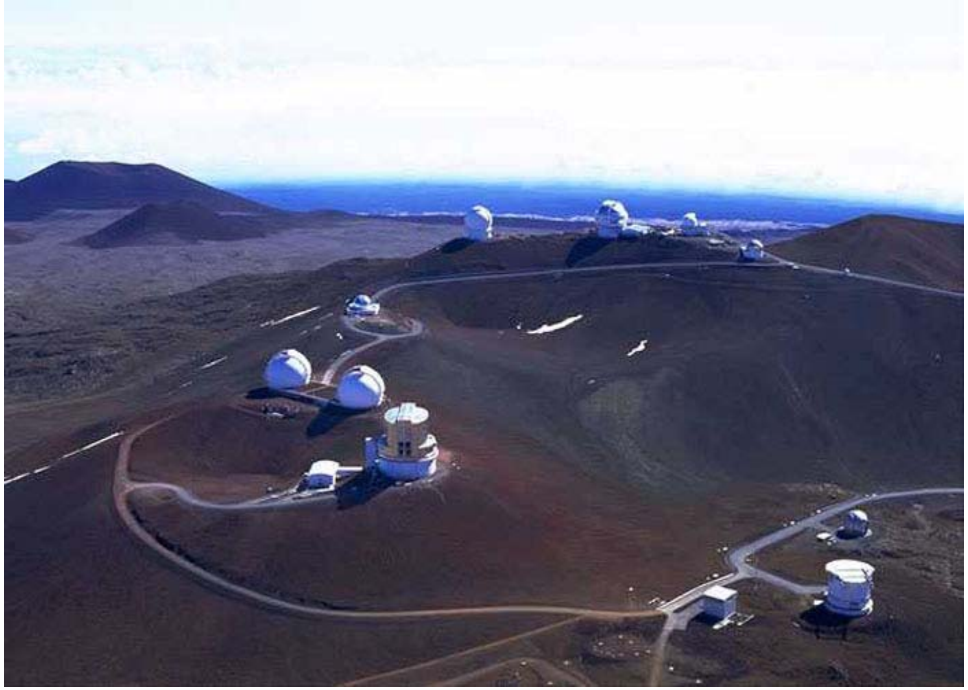
= best resolution a telescope can achieve

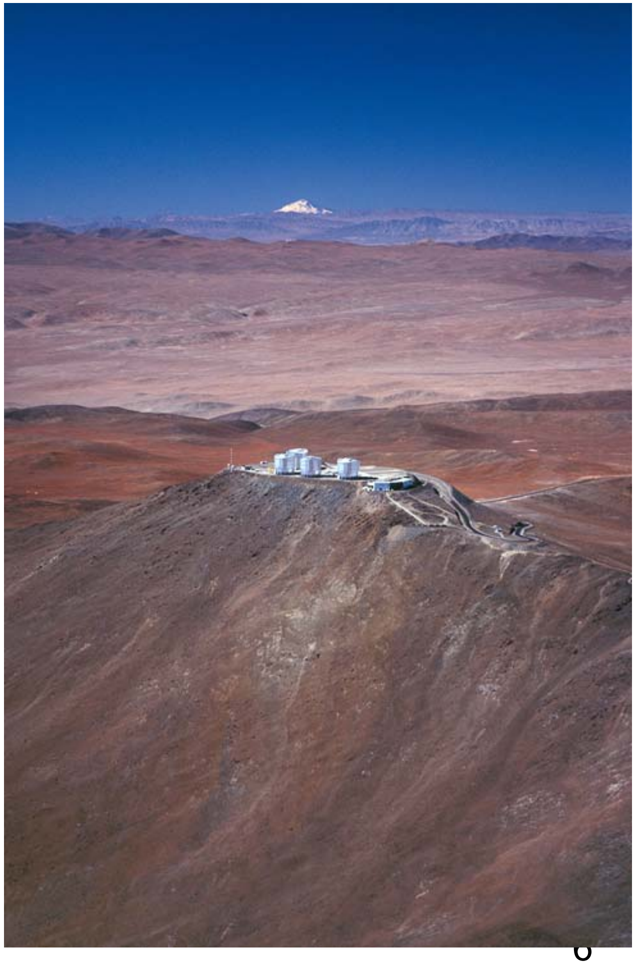
→Improve resolution by building bigger telescopes or working at shorter wavelengths

Best resolution, θ_{min} = diffraction limit hard to achieve in practice

<u>Seeing:</u>

atmospheric turbulence distorts image → Mauna Kea, Cerro Paranal, Hubble etc, AND adaptive optics





Other sources of image distortion

- Chromatic aberration (refractors only)

  For a lens, $1/f_\lambda = (n_\lambda - 1)(1/R_1 + 1/R_2)$

  $\therefore F_{red} \neq F_{blue}$ and foci are also different

  correct with other lenses
- Spherical aberration (mirrors or lenses)
  - F changes with distance from axis
  - carefully ground paraboloids help
- Coma
  - for paraboloids, f a function of θ, and $d\theta/dy = 1/f$
  - elongated images off-axis

Illumination and Focal ratios

- Light-gathering power of telescopes measured by J = illumination = energy/sec/area of image

  amount of light (energy/sec) $\propto$ aperture area = $\pi(D/2)^2$

  = $\pi D^2/4$, where D is telescope diameter

  Recall that $y = f\theta$, $\therefore$ image area $y^2 \propto f^2$

  $\therefore$ Illumination J = energy/sec/area of image $\propto D^2/f^2$
- Focal ratio $F \equiv f/D$ by definition and $J \propto 1/F^2$

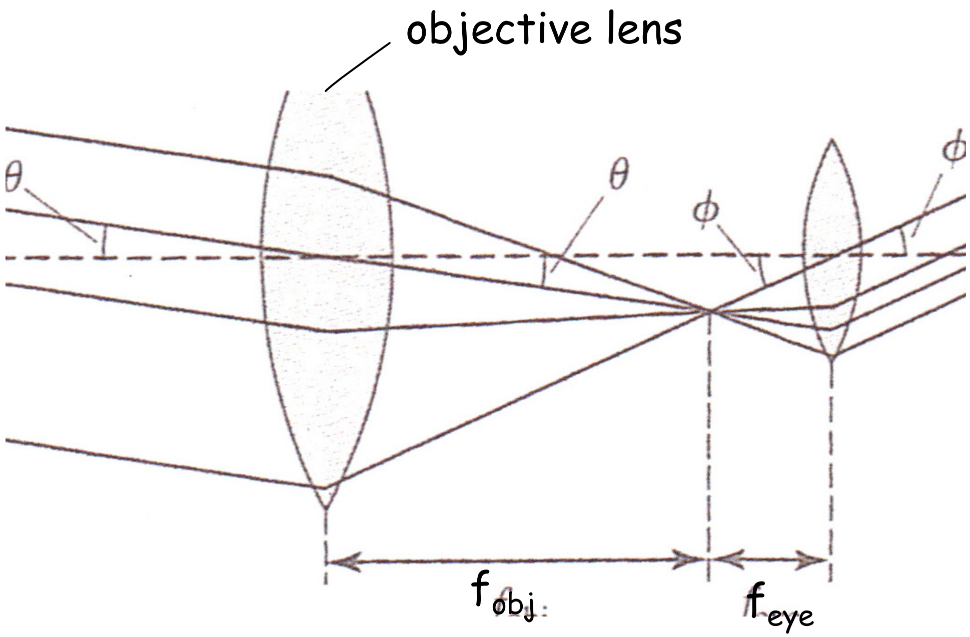
- Since $\theta_{min} = 1.22\ \lambda/D$ and $J \propto D^2/f^2$ larger telescopes improve both resolution and illumination

Note: focal ratios written as f/F

e.g. Keck F = 17.5m/10m = 1.75 → 10m f/1.75 primary mirror

Hubble: 2.4m f/24 primary (1200 Å - 1μm) – no atmosphere!

Refracting telescopes -disadvantages

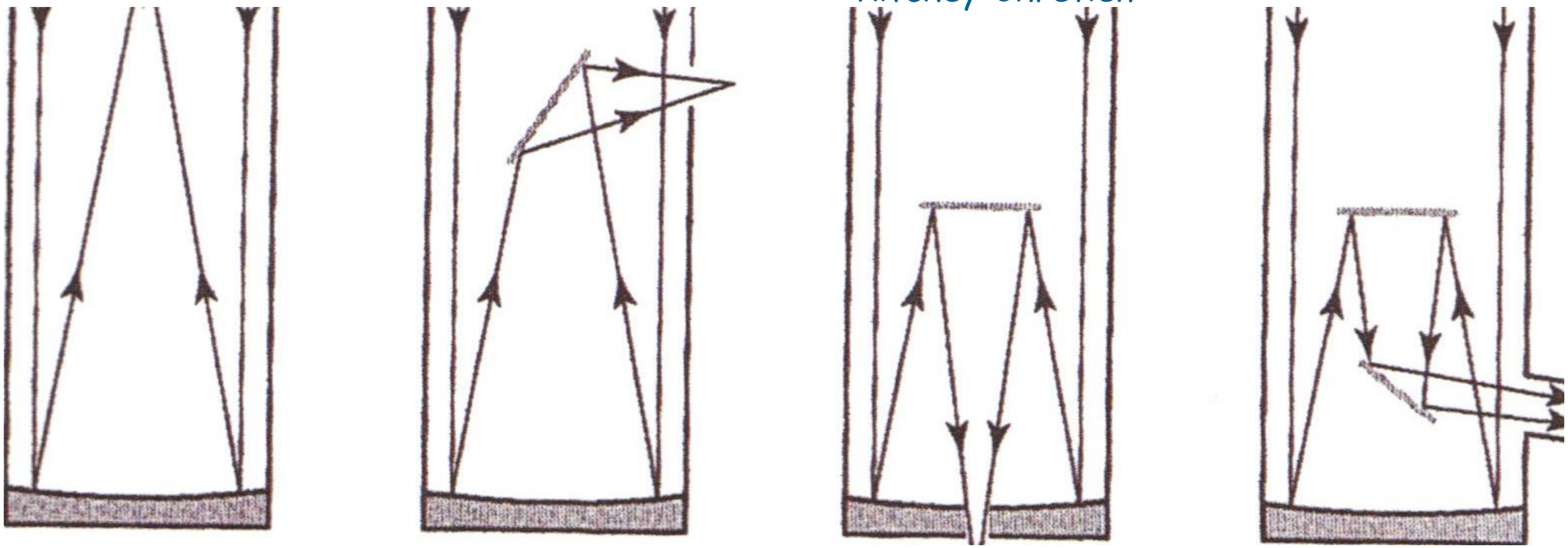


- Chromatic aberration
- $J \propto D^2/f^2$ – increase D to increase illumination, BUT increases problems of supporting lens (only at edges)
- Lens deforms w. gravity; difficult to create *perfect* lens; slow thermal response also problematic
- Long focal length limits detectors at end; torques

Most telescopes now reflectors

- Only one precision surface required
- Honeycomb behind reflecting surface reduces mass
- With mirror supported behind (not edges) eliminate distortions due to gravity and thermal effects
- No chromatic aberration

hyperbolic secondary
Ritchey-Chrétien



Prime focus
Palomar f/3

Newtonian focus
f/3, 5/10

Cassegrain focus
f/8…f/15
Good for instruments

Coudé
f/30
30% efficient

Radio telescopes (sub-millimeter –centimeter wavelengths)

- Radio waves reflected from parabolic surface (dish) to secondary mirror
- As in optical, radio waves subsequently routed to detectors, then amplified, processed
- Measure energy/sec/Hertz (unit frequency)

= flux density S_ν watts/m^2/Hz

(usually integrated over collecting area & bandwidth)

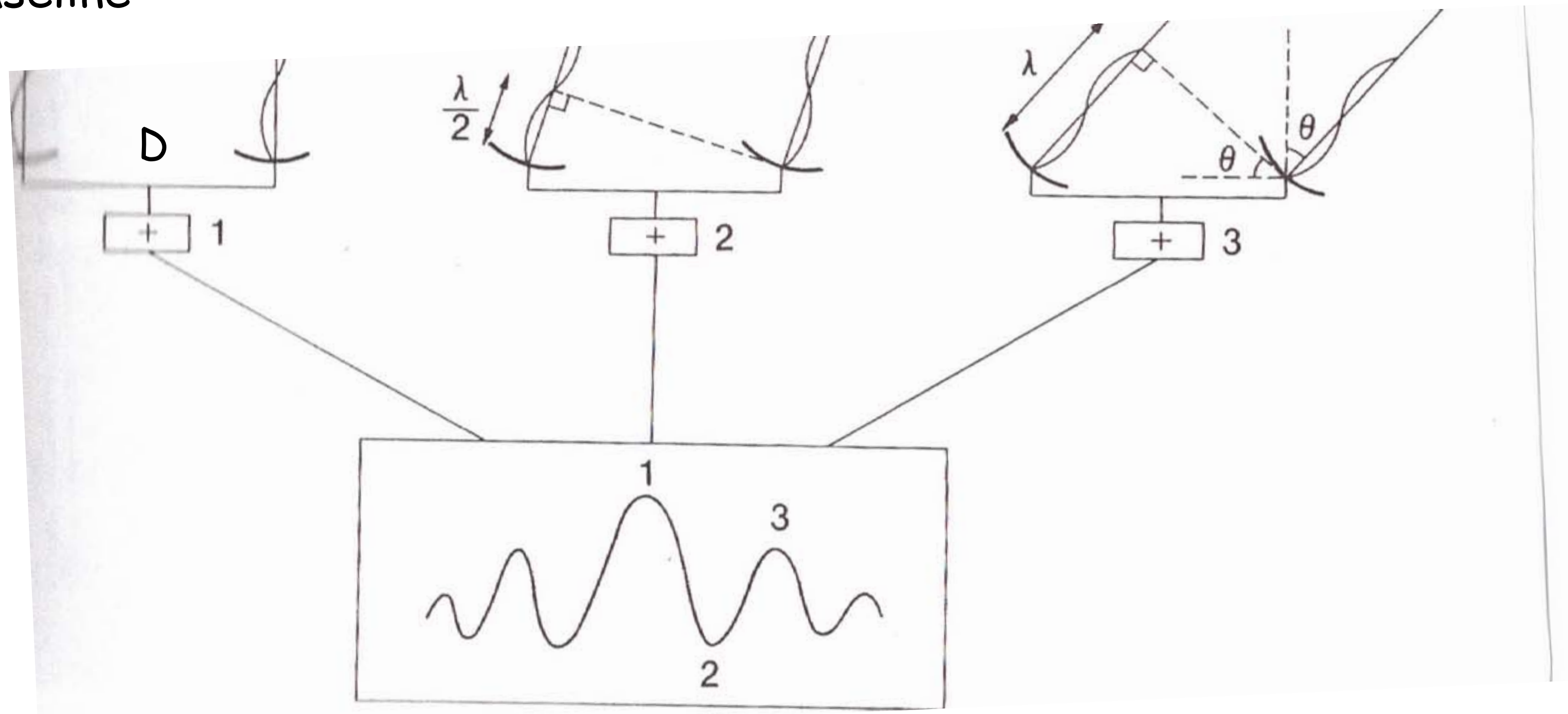
New unit! Jansky: 1 Jy = 10^{-26} W m^{-2} Hz^{-1}

- Optimal resolution achievable: $\theta_{min} = 1.22\ \lambda/D$

∴ need impossibly large telescopes OR interferometers

At longer (microwave, radio) wavelengths interferometers needed for best resolution

D = baseline



constructive interference (1 & 3), path difference $L = n\lambda$

destructive (2), $L = n\lambda/2$, where $L/D = \sin\theta \approx \theta$

$\therefore$ best resolution $\theta_{min} = \lambda/D$

(compare with Rayleigh criterion for single telescopes)

Astronomical Coordinates

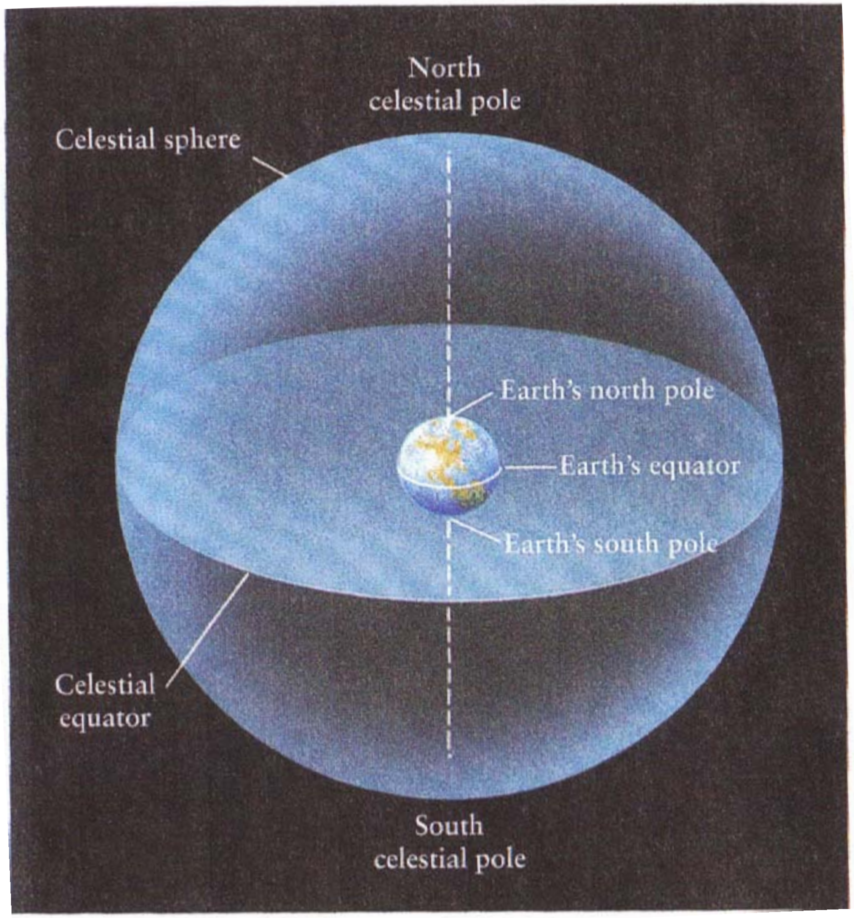
- Rooted in geocentric universe concept but still works!
- Failed to explain motions of planets ("wanderers")

- Concept of planets orbiting Sun and at different distances due to Copernicus (1543)
  - Venus, Mercury (Inferior Planets) – never observed more than 28° or 47° respectively E or W of the Sun
  - Mars, Jupiter, Saturn (Superior Planets) sometimes as much as 180° from Sun = opposition

- Detailed motions of planets remained problematic

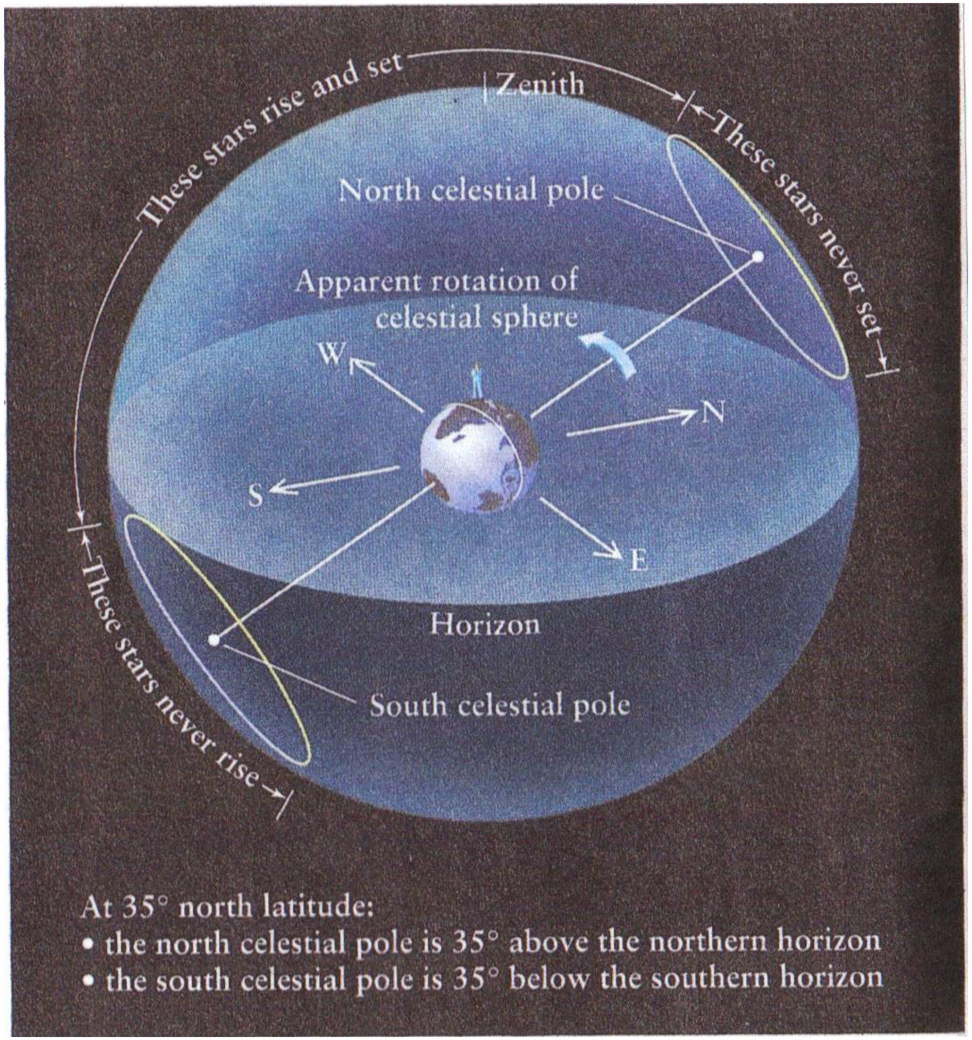
  fundamental error is assuming circular orbits

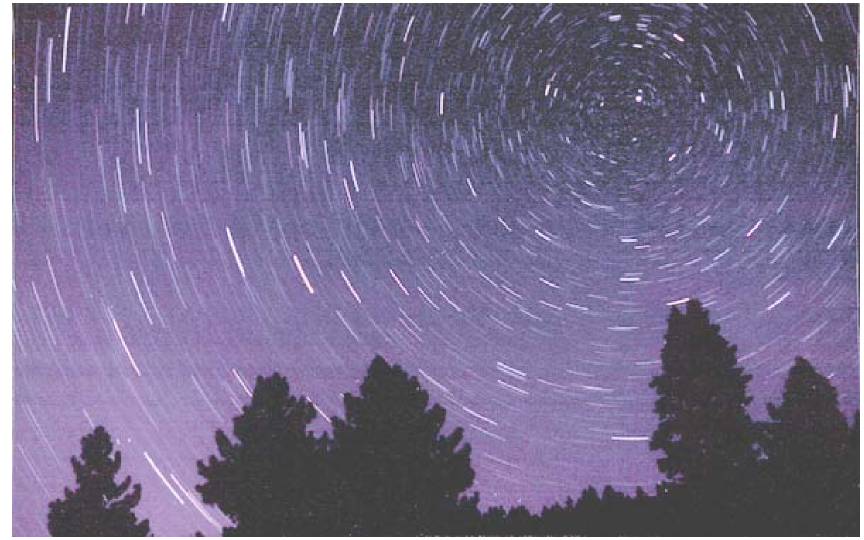
Celestial Sphere



- Astronomical observations based on earth-centered reference frame
- Have to take into account
  - Diurnal rotation
  - Annual motion around Sun
  - Wobble of rotation axis
  - Stars move relative to one another
- Celestial sphere enables "directional" measurements i.e. positions only

From 35° N Latitude

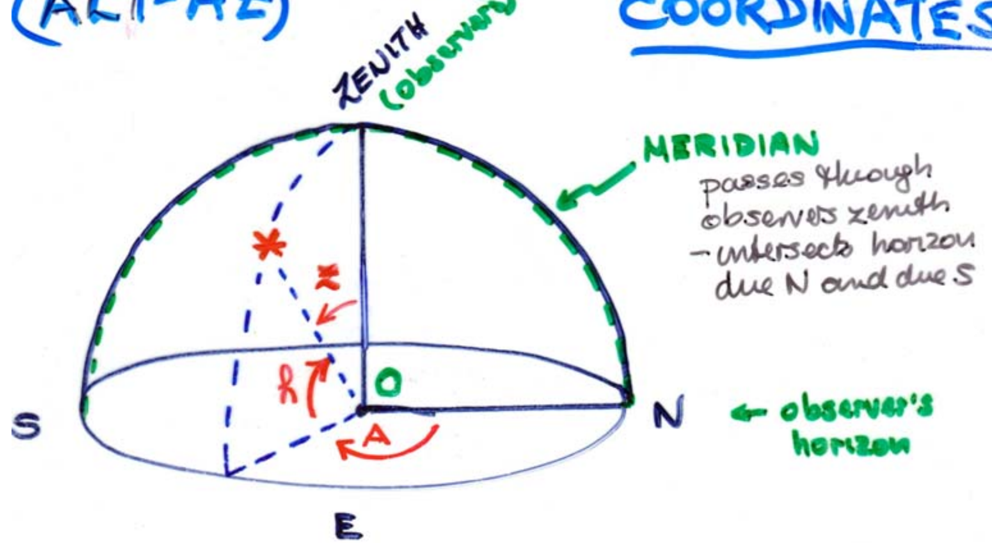




Circumpolar stars within 35° of pole

As Earth turns from west to east, celestial sphere appears to turn from east to west

ALTITUDE AZIMUTH (HORIZON) (ALT-AZ) COORDINATES



- altitude h = distance from horizon to object measured along great circle through object and zenith
- z = distance from zenith to object along same circle

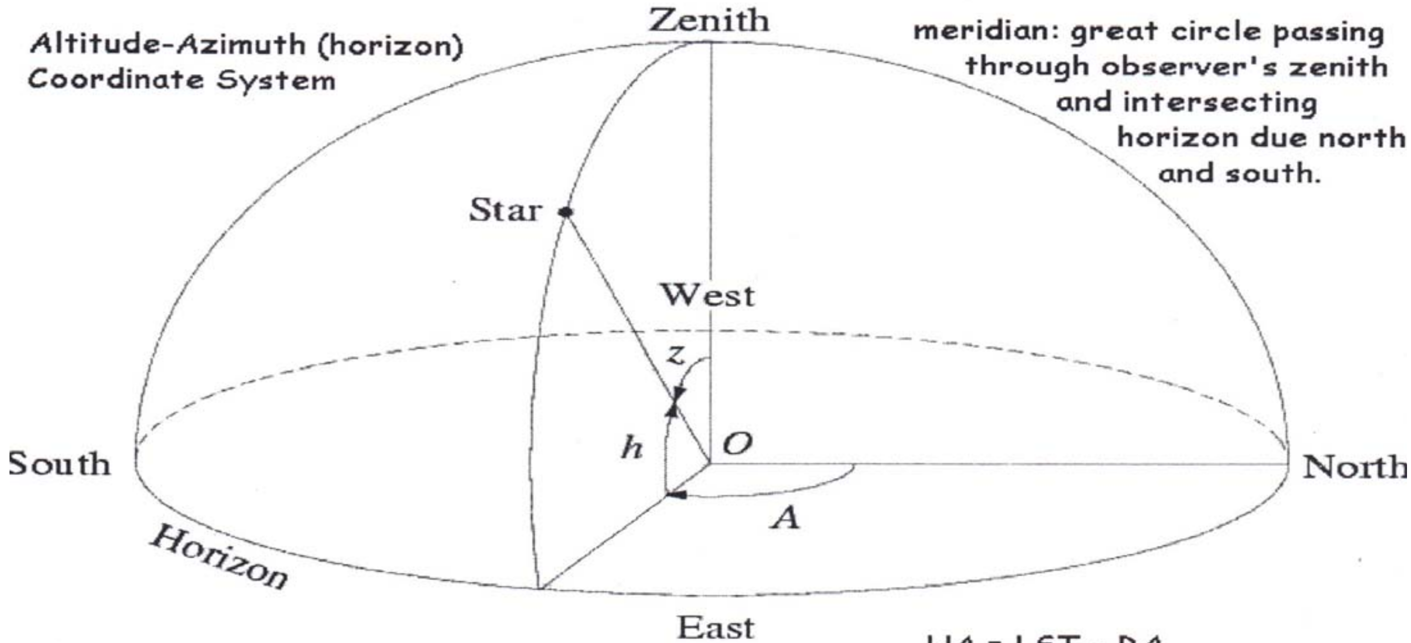
$$z + h = 90°$$

- azimuth A = angle measured along horizon east from north
- meridian = great circle passing through observer's zenith and intersecting horizon at due north and due south

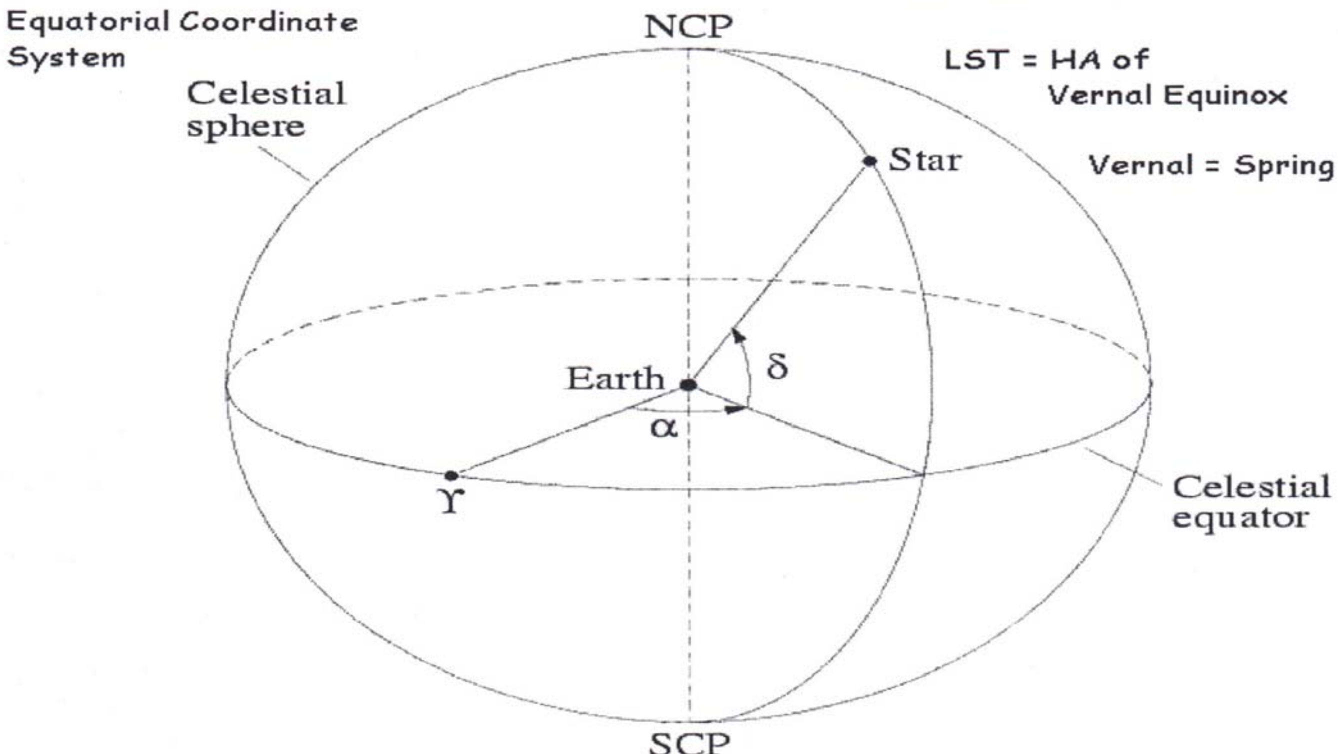
DISADVANTAGES:

h,A depend on observer's location; change as earth rotates daily

Stars rise ~ 4 minutes earlier each night – positions different each day


Altitude-Azimuth (horizon)
Coordinate System
Zenith
meridian: great circle passing
through observer's zenith
and intersecting
horizon due north
and south.
Star
West
z
h
O
South
North
A
Horizon
East

HA = LST - RA


Equatorial Coordinate
System
NCP
LST = HA of
Vernal Equinox
Celestial
sphere
Star
Vernal = Spring
δ
Earth
α
ϒ
Celestial
equator
SCP

Equatorial Coordinate System

- A bit like latitude and longitude
- Declination δ (° ′ ″) , Right Ascension α (h m s)
- -90° < δ < +90° and α 0^h – 24^h
- RA = 00^h 00^m 00^s on Vernal Equinox
- Sun is then on meridian at noon i.e RA 00^h 00^m 00^s

- Sun's path across celestial sphere = ecliptic
- Due to 23.5° tilt of Earth's axis, does not coincide with celestial equator
- Each hemisphere of Earth alternately points towards or away from Sun during a year

Solar Motion parallels Seasons