AS1001
STARS and ELEMENTARY ASTROPHYSICS

Keith Horne
Room 315a
kdh1@st-and.ac.uk
star-www.st-and.ac.uk/~kdh1/sea/sea.html

STARS AND ELEMENTARY ASTROPHYSICS

- Synopsis
  1. Telescopes and Instruments
  2. Distances to Stars
  3. Electromagnetic Radiation
  4. Stellar Astrophysics
  5. Motions of Stars in Space

  (Kutner's "Astronomy", parts of Chapters1,2,3,4,5)

- ASTRONOMY
  - studies of the stars, and by extension,
  - studies of the Universe
- STARS
  - points of light in night-time sky
  - grouped into CONSTELLATIONS

    (not usually physical groups - just chance projections of stars onto the sky as seen by us from Earth)
  - brighter and fainter stars

  Hot stars blue, cool stars red

- STARS
  - how far away are they?
  - do they all have the same "intrinsic" brightness? (NO!)
  - how do we know what stars are?
  - is the Sun a star? (YES!)

We use telescopes+associated instruments to measure starlight, and apply physics to build computer models of stars, to answer these questions.

[Concepts you will learn in Stars and Elementary Astrophysics are fundamental to the whole subject of astronomy. The ideas (e.g. distances, motions) apply to stars, extend to galaxies, and then the Universe, in other parts of AS1001.]

1. TELESCOPES AND INSTRUMENTS

To collect and record electromagnetic radiation (light) from astronomical sources (planets, stars, nebulae, galaxies)

Transparency of the Earth's atmosphere to radiation

High energy
short wavelength

Low energy
long wavelength

Observing through the Earth's atmosphere

- 2 main "transparent" regions
  1. Optical Window - wavelengths λ 300-800 *nm*
     (*nm* = nanometre = 10^{-9} *m*)
     human eye λ 400-700 *nm*
     violet - red
  2. Radio Window - wavelengths 1 *mm* - 20 *m*

The infrared region - (heat) - wavelengths 1 - 10ì m
(*mm* = micrometre = 10^{-6} *m* = micron)
- is only partially transparent due to water vapour
- best observed from dry high-altitude sites

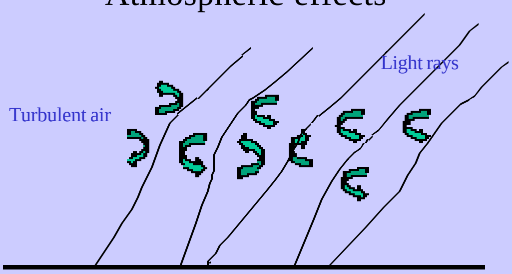
Earth's atmosphere is OPAQUE to :
gamma-rays (Ó-rays), X-rays, the ultraviolet (UV) region, and the far-infrared to millimetre regions of the electromagnetic spectrum.

Such radiation from astronomical sources is observable only above Earth's atmosphere - hence the need for spacecraft in orbit about the Earth.

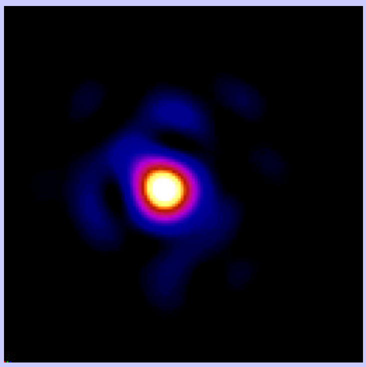
OPTICAL & INFRARED RADIATION

Effects of Earth's atmosphere
- SCINTILLATION
  - stars twinkle - turbulent layers of atmosphere, at different temperatures and densities, deflect the incoming light rays
  - extended objects - planets - twinkle less

Atmospheric effects



Scintillation = brightness changes
Seeing = angle changes

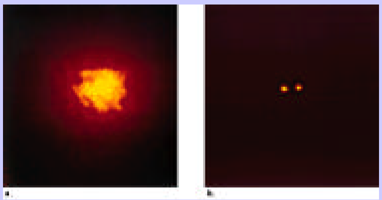


- a telescope collects light over a much larger area than the eye - hence reduces scintillation
- BUT the image of a point source seen through a telescope appears to be smeared, made up of vibrating speckles - a phenomenon called “SEEING”
- good seeing
  - image diameter ~ 1 arc second
    (best conditions at sea level St Andrews ~ 2 arcsec
    best astronomical sites ~ 0.5 arcsec

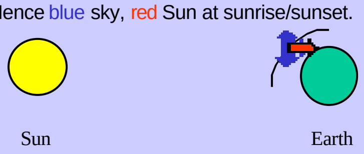
  1 arcsec = 1/3600 degree = 1 penny / 4 km

  spacecraft missions not affected (e.g. Hubble Space Telescope) - image diameter ~ 0.05 arcsecond

The seeing disc and the use of adaptive optics to unblur images



- Atmospheric EXTINCTION
- reduction in flux of radiation by scattering and absorption by atoms, molecules in the atmosphere
- scattering - randomize direction
- absorption - remove energy
- stronger effect at short wavelengths
- Hence blue sky, red Sun at sunrise/sunset.



- <u>Best astronomical sites</u> in world are above the main cumulus cloud layer (2000 *m*) and with very low rainfall (< 250 *mm yr*$^{-1}$) and excellent seeing
  - perfect clear sky (no clouds) ~70% of year
  - useable conditions ~95% of year

- Mauna Kea, Hawaii (4000 *m* above sea level)
- La Palma, Canary Islands (2500 *m*)
- Northern Chile (2500 *m*)

  all remote from cities, light pollution, etc.

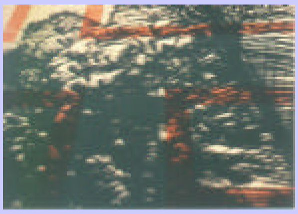
- For <u>RADIO ASTRONOMY</u>
  much less critical, except for interference from microwave ovens, electrical power lines, radio, television, mobile phones, …..

- UK: Jodrell Bank, Cambridge
- Netherlands
- Germany many large steerable dishes
- U.S.A. + large arrays
- Australia

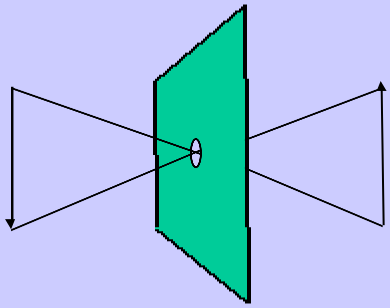
<u>Optical and Infrared Telescopes</u>

- collect light over a large area, to study very faint sources
- magnify the apparent angular size of sources, for better resolution
- accurate positions of sources in the sky

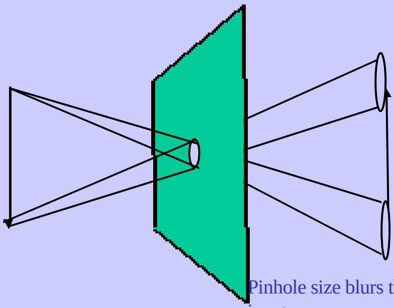
Pinhole camera images



Pinhole camera

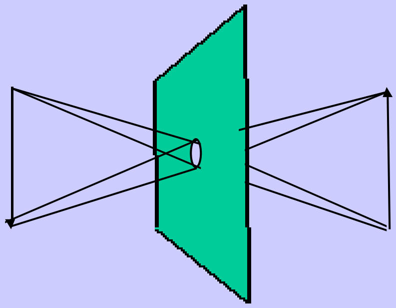


Problem with pinhole camera



Pinhole size blurs the image

Solution: insert a lens



How a lens works

By slowing light down

REFRACTORS

objective lens
+ eyepiece
largest:
1.0 m Yerkes (1888)
now obsolete

REFLECTORS

mirror systems
or
combinations of mirrors and lenses
largest:
10.0 m Keck
(Hawaii 1992)
planned: 30m ELT
100m OWL

net result is the same:
an imaging system brings radiation from a distant source (parallel rays of light) to a focal plane where the image may be recorded directly or entered into an analysing instrument (including the eye)

Problems with Refractors

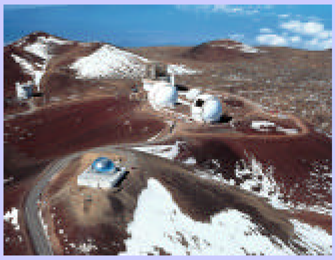
Large lenses hard to make (more expensive).

Lenses must be supported only on their rim.

Lens focal length depends on wavelength.

All large telescopes today are reflectors.

Aerial view of the summit of Mauna Kea, Hawaii

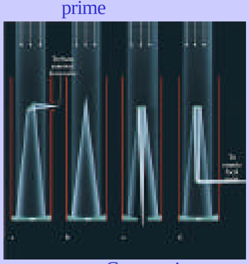


Keck 10-metre optical telescope

Various designs of reflector telescopes

prime

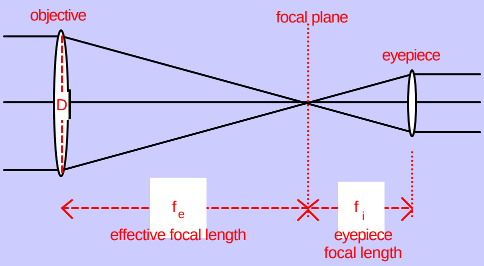
Newtonian



Neysmith or Coude

Cassegrain

Telescope Optics



telescope aperture = diameter *D* of objective

- FOCAL RATIO n = f_e/D, written as f/n

e.g. D = 100 *cm*, f_e = 300 *cm*, f ratio is f/3

f_e = 2000 *cm*, f/20

the f/ ratio measures how rapidly the beam converges to a focus

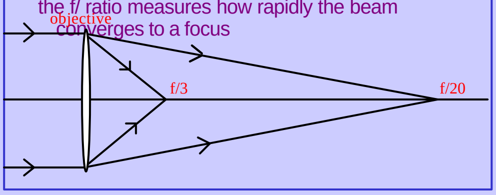


Image of an extended source

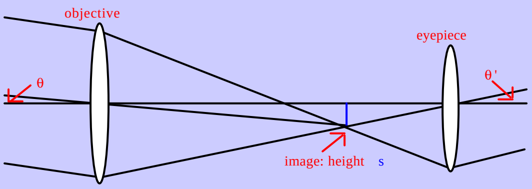
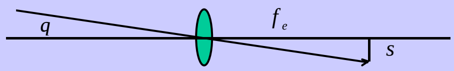


Image size



$$s = f_e \tan q \cong f_e q$$

- *example* $f_e = 300$ cm

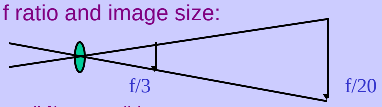
$$q = 1 \text{ arcmin} \times \frac{1^\circ}{60 \text{ arcmin}} \times \frac{ð \text{ radian}}{180^\circ}$$

$$s = 300 \text{ cm} \times \frac{1^\circ}{60 \text{ arcmin}} \times \frac{ð \text{ radian}}{180^\circ} = 0.087 \text{cm}$$

- *example 2*

$f_e = 3000$ cm $q = 1$ arcmin $s = 0.87$ cm

- f ratio and image size:

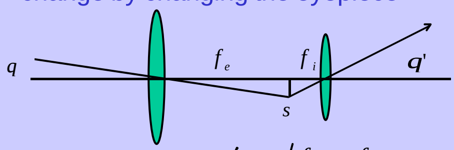


- small f/ ⇒ small images
- large f/ ⇒ large images
- Fast / Slow optical systems

FAST (small f/) concentrates light into small image.
-- short exposure times
-- wide field of view
SLOW (large f/) spreads light over larger image.
-- longer exposure times needed
-- narrow field of view

Magnification

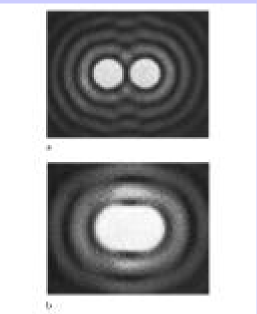
- change by changing the eyepiece



$$\text{magnification} = \frac{q'}{q} \cong \frac{s/f_i}{s/f_e} = \frac{f_e}{f_i}$$

$$= \frac{\text{effective focal length}}{\text{eyepiece focal length}}$$

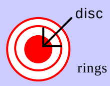
Resolving a double star



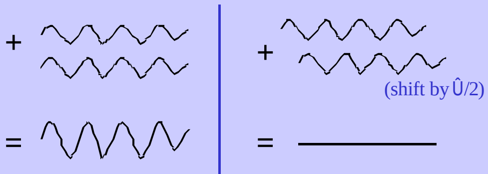
Angular Resolution

- the minimum angular separation of two sources on sky that may be seen as two separate sources in telescope
- seeing limit (e.g. 1 arcsec)
- diffraction limit (e.g. l/D radians) (caused by diffraction at edge of telescope aperture)

Airy pattern:

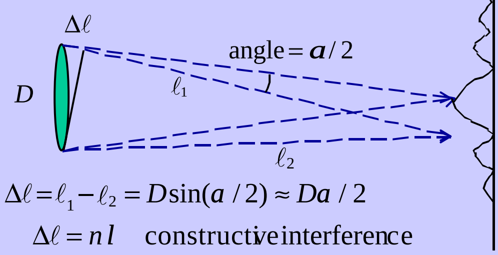


Interference of light waves



constructive (double amplitude) | destructive (zero amplitude)

Diffraction limit



$$\Delta\ell = \ell_1 - \ell_2 = D\sin(a/2) \approx Da/2$$

$\Delta\ell = n\,l$ constructive interference

$\Delta\ell = (n+\frac{1}{2})\,l$ destructive

$$a \approx l / D$$

- "diffraction-limited" image
  typically < 0.1 arcsec at optical wavelengths
- Rayleigh's criterion: angular resolution

$$a = 1.22\frac{l}{D} \text{ radians} \cong 2.5\times10^5 \frac{l}{D} \text{ arcsec}$$

Note: D and Û in the same units
D = diameter of aperture (main mirror) of telescope
Û X500 nm (wavelength of optical light)
Ñ ~ 1 arcsec for D~0.125 m.
X0.03 arcsec for D~4 m.

At Radio Wavelengths

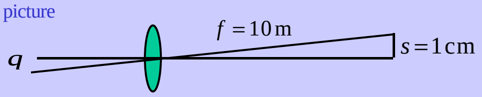
l_{radio} = 20 cm ~ 400,000 ´ $l_{optical}$

- For 1 *arcsec* resolution,
  . need *D* ~ 50 *km* !
  . (not very realistic)

- Solution: INTERFEROMETRY
  . (later)

Problem Solving

picture



equation $s = f\sin q \approx fq$

rearrange $q = s/f$ check dimensions

numbers with units $q = \frac{1\text{ cm}}{10\text{ m}} \times \frac{1\text{ m}}{100\text{ cm}} = 10^{-3}$ radians

calculate

factors to change units $\times \frac{180^\circ}{p\text{ radians}} \times \frac{60\text{ arcmin}}{1^\circ} = 3.4$ arcmin

Problem Solving

1. Draw a simple picture (label with symbols)
2. Write an equation (check dimensions)
4. Re-arrange the equation
5. Insert numbers with units
6. Multiply by factors to obtain correct units
7. Does the result make sense?

Astronomical Instruments

Measure properties of incoming light

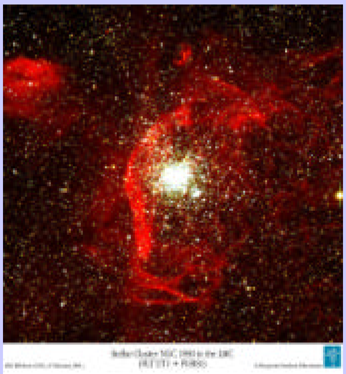
- Imaging - direction
- Photometry - brightness
- Spectroscopy - wavelengths
- Polarimetry - linear/circular polarisation
- Timing - variations in all of the above

- ***direct cameras*:** record an image of an area of sky with stars, galaxies, …
  - Schmidt telescopes:
    f/2 - f/3, large fields 6° ´ 6°
  - photographic plates
  - reflectors: prime focus ~ f/3
    Cassegrain focus ~ f/10
    fields < 1°, better image scale
  - electronic detectors (CCDs)

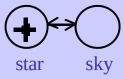
- *photographic plates*
  --glass coated on front side with photographic emulsion
  - large area (e.g. 35 ´ 35 cm)
  - low efficiency (1-2%)
    98% of light not recorded
  - negatives digitized by laser scanner
  - e.g. Palomar Digital Sky Survey
  - UK Schmidt Telescope Survey

- *electronic detectors*
  - Charge-Coupled Device (CCD)
  - silicon chip; array of light-sensitive squares
    - PIXELS (+readout electronics)
  - pixel size ~15 ´ 15 *mm*
  - format ~ 1024 ´ 1024 pixels
    up to 4096 ´ 4096 pixels
  - small area : postage stamp
  - ~ 75-90% efficiency
  - digital images read direct from CCD
  - expensive

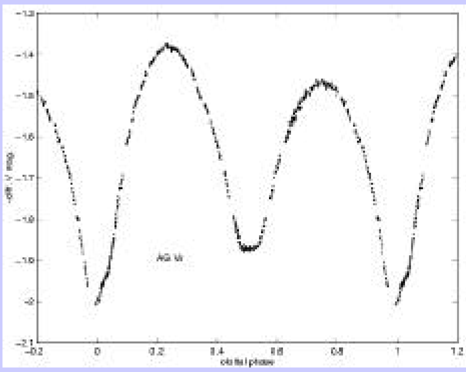
A Charge-Coupled Device, CCD



- photometry:
  - measure apparent brightnesses of sources
  - filters select a range of wavelengths
  - narrow~1 nm broad~100 nm
- photomultiplier tube
  - ~20% efficiency
  - counts individual photons high speed (e.g. milliseconds)
  - one star at a time
  - (focal plane pinhole)

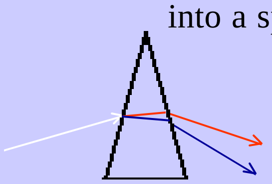


- CCD camera:
  - < 1% accuracy
  - >10s time resolution
  - ~10,000 sources per CCD image
- digitized photographic plates
  - 5-10% accuracy
  - exposure time ~ hours
  - millions of sources per Schmidt plate



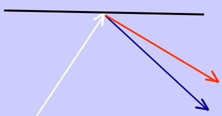
- ***spectroscopy***:
  - spectrograph / spectrometer with prism or diffraction grating to disperse light into a spectrum
  - record spectrum with a CCD
  - (***polarimetry***, ***spectropolarimetry*** use instruments together with a polariser)

Dispersing light into a spectrum

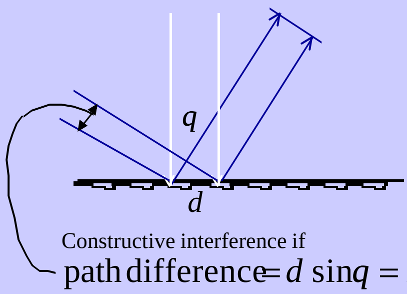


Prism

Grating



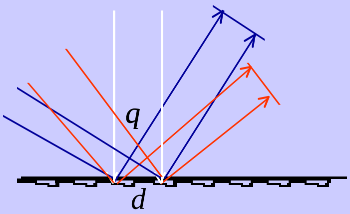
Diffraction Grating



Constructive interference if

path difference $= d \sin q = m l$

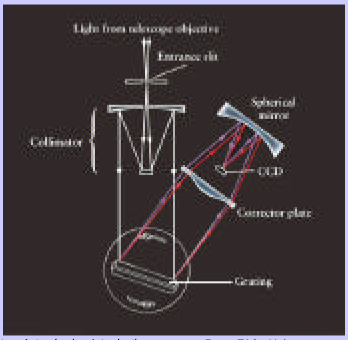
Diffraction Grating



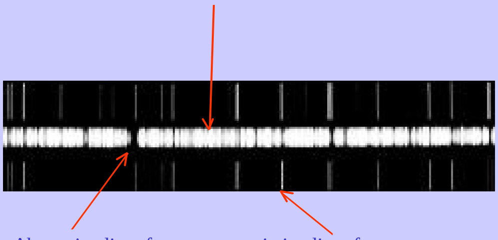
Constructive interference if

$$\text{path difference} = d\sin\theta = m\lambda$$

A typical spectrograph



Spectrum of a star

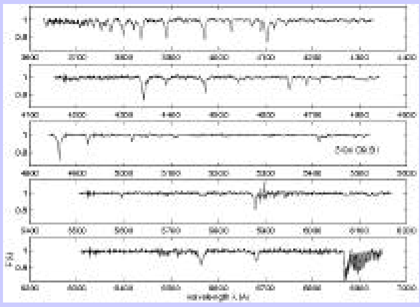


Absorption lines from star's atmosphere

emission lines from a calibration source

Spectrum of a star

blue



red

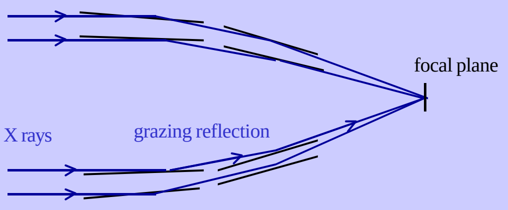
- Ultraviolet studies - from satellites
  - reflecting telescopes with smoother mirrors
  - CCDs not sensitive to ultraviolet, so use photon-counting electronic detectors
  - Hubble Space Telescope (HST)
  - 0.05 arcsec resolution (after repair!)
  - 2.4 metre diameter mirror
  - UV spectrometer; direct imaging
  - (also optical and infrared)
  - EUVE = Extreme UltraViolet Explorer
  - FUSE = Far UltraViolet Explorer

Telescopes and detectors for high-energy radiation

- gamma rays - γ rays - $\lambda < 0.01$ *nm* (10^{-11} *m*)
- X-rays -- hard: $\lambda \sim 0.01 - 0.1$ *nm*

  soft : $\lambda \sim 0.1 - 10$ *nm*
- *PROBLEM:*
  - will not reflect from ordinary mirrors
  - nested rings of highly polished mirrors using GRAZING REFLECTION

Schematic X-ray Telescope



- detectors:
  - g-rays
    - scintillation detectors (e.g. NaI crystal)
    - several layers convert g-rays by photoelectric effect into visible light detectable by photomultiplier
  - X-rays
    - now mainly solid-state detectors like CCDs
    - hence measurable current of electrons proportional to X-ray flux density

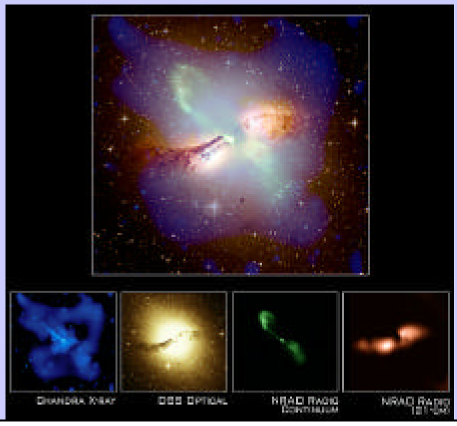
- recent satellites for high-energy radiation studies:

  Compton gamma-ray observatory - 1991
  ROSAT (Röntgen satellite) - X-ray studies - 1992
  YOKHOH - X-ray studies of the Sun - 1993
  RXTE (Rossi X-ray timing explorer) - 1996
  Chandra - X-ray spectroscopy - 1999
  XMM-Newton - X-ray imaging - 1999

Multi-Wavelength Astrophysics

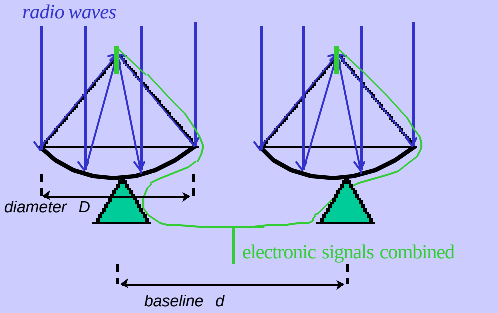
- gamma-ray --- relativistic gas $(>10^9\,\mathrm{K})$
- x-ray ------------ hot gas $(10^{6-8}\,\mathrm{K})$
- ultraviolet ------ hot stars $(10^{4-5}\,\mathrm{K})$
- optical ---------- cool stars $(10^{3-4}\,\mathrm{K})$
- infrared --------- cool gas,dust $(10-100\,\mathrm{K})$
- millimetre ------ Big Band afterglow $(3\,\mathrm{K})$
- radio ------------ non-thermal radiation

Each wavelength gives a different picture



The Very Large Array (VLA) Radio Interferometer

Radio Telescopes and Interferometry



Resolution of Radio Telescope

diameter $D = 20$ m

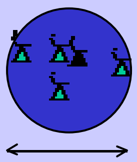
$$\frac{\lambda}{D} \approx \frac{20\text{ cm}}{20\text{ m}} \times \frac{1\text{ m}}{100\text{ cm}} \times \frac{180^\circ}{\pi\text{ radian}} = 0.6^\circ$$

Resolution of Radio Interferometer

baseline $d = 20$ km

$$\frac{\lambda}{d} \approx \frac{20\text{ cm}}{20\text{ km}} \approx \frac{0.6^\circ}{1000} \times \frac{3600\text{ arcsec}}{1^\circ} = 2\text{ arcsec}$$

Very Long Baseline Interferometry VLBI



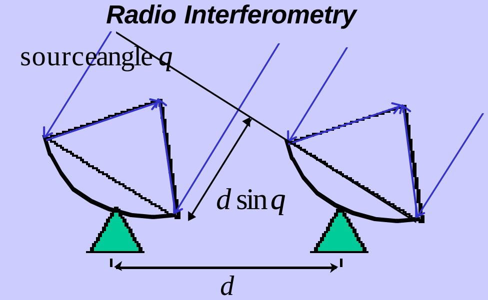
Linked Radio Telescopes across the Globe

longest baseline $d \approx 10^4$ km

$$\frac{\lambda}{d} \approx \frac{20\text{ cm}}{10^4\text{ km}} \times \frac{1\text{ km}}{10^5\text{ cm}} \times \frac{180^\circ}{\pi\text{ radian}} \times \frac{3600\text{ arcsec}}{1^\circ}$$

$$= 0.004\text{ arcsec} = 4\text{ milliarcsec}$$

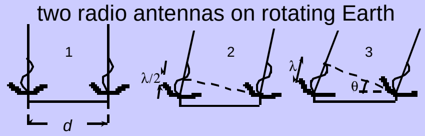
Radio Interferometry



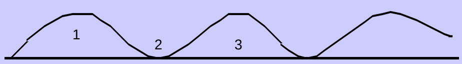
constructive interference when $d \sin\theta = n\lambda$

Radio Interferometry

two radio antennas on rotating Earth



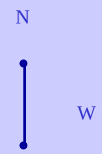
constructive interference when $d \sin\theta = n\lambda$



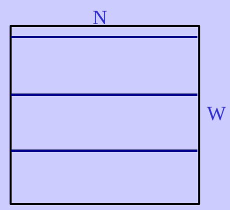
Interference pattern recorded as angle changes in time

Aperture Synthesis

2 telescopes
1 baseline



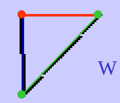
possible source directions



$$\sin\theta = n\lambda / d$$

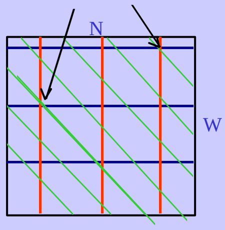
Aperture Synthesis

3 telescopes
3 baselines



N telescopes
N(N-1)/2 baselines
less and less ambiguity

possible source locations



$$\sin \theta_{1,2,3} = n\lambda / d_{1,2,3}$$

examples:

- UK MERLIN
  (Jodrell Bank, Cambridge, Rutherford Lab.)
  - resolution ~ 0.01 arcsec
- USA Very Large Array (VLA)
  - Y-shaped array, each arm up to 21 km long, effective diameter 35 km
  - ~ 0.1 arcsec
- Very Long Baseline Interferometry (VLBI)
  - (Australia, Europe, USA, ...)
  - needs synchronised, highly accurate timing, major data storage and computer processing
  - ~ 0.1 milliarcsec

Optical /Infrared Aperture Synthesis

very difficult because wavelengths much shorter.

$$\frac{\lambda}{d} \approx \frac{5\times10^{-7}\,\text{m}}{100\ \text{m}} \times \frac{2\times10^{5}\,\text{arcsec}}{\text{radian}} = 0.001\,\text{arcsec}$$

European Southern Observatory (ESO)

- Very Large Telescope Interferometer (VLTI)
  - Four 8 metre telescopes (now)
  - + many 1.5m telescopes (soon)