Radio Astronomy

MSc. course

Lecture 2a,2b (of 14):

Radio Telescopes: antennas, paraboloids, performance

Prof. Mike Garrett
(ASTRON/Leiden/Swinburne)

Acknowledgements

I've tried to steal the best ideas and bring them together into a coherent picture that broadly covers radio astronomy - the technique and the science.

I acknowledge the following sources of information:

Publications:

Napier, SIRA Chapter 3

Presentations:

Prestage et al. "Adjusting the GBT surface"
Masao Saito "Antenna" - 2007 winter school

For more information on this course, see:

www.astron.nl/~mag/dokuwiki/doku.php?id=radio_astronomy_course_description

Re-cap: lecture 1

Prehistory:

1870's: James Clerk Maxwell predicts existence of electromagnetic radiation with any wavelength!
1888: Heinrich Hertz demonstrates transmission and reception of radio waves

Early pioneers:

1932: Karl Jansky discovers cosmic radio waves from the galactic centre (USA)
1937-1944: Grote Reber's First Surveys of the Radio Sky (USA)
1942: Sun discovered to be a radio source by J.S. Hey (UK)
1936-1945: Development of radar before and during world war II e.g. Sir Bernard Lovell
1944: Prediction by Henk van der Hulst and Oort (NL) of neutral Hydrogen spectral line emission at 1.4GHz.
1951: Detection of neutral Hydrogen Ewen & Purcell (USA) and van der Hulst & Oort (NL)
1956/7: Construction of the first large steerable telescopes (Dwingeloo-NL, Jodrell Bank-UK...)

Major discoveries:

1960-63: Radio sources identified with blue quasi-stellar objects with huge recession velocities
1960s: First radio interferometers constructed; Aperture Synthesis developed (Ryle, UK) - Noble Prize
1965: Cosmic Microwave Background (CMB) detected (Penzias & Wilson, USA) - Noble Prize
1967: Pulsars (rotating neutron stars) discovered by Jocelyn Bell & Tony Hewish (UK) - Noble Prize

Large scale radio telescope facilities:

1967: First successful transatlantic Very Long Baseline Interferometery observations.
1970: Westerbork Synthesis Array telescope starts operations (NL)
1976: Very Large Array (VLA) becomes operational (USA) etc. etc.

What else makes radio astronomy "special" - 1

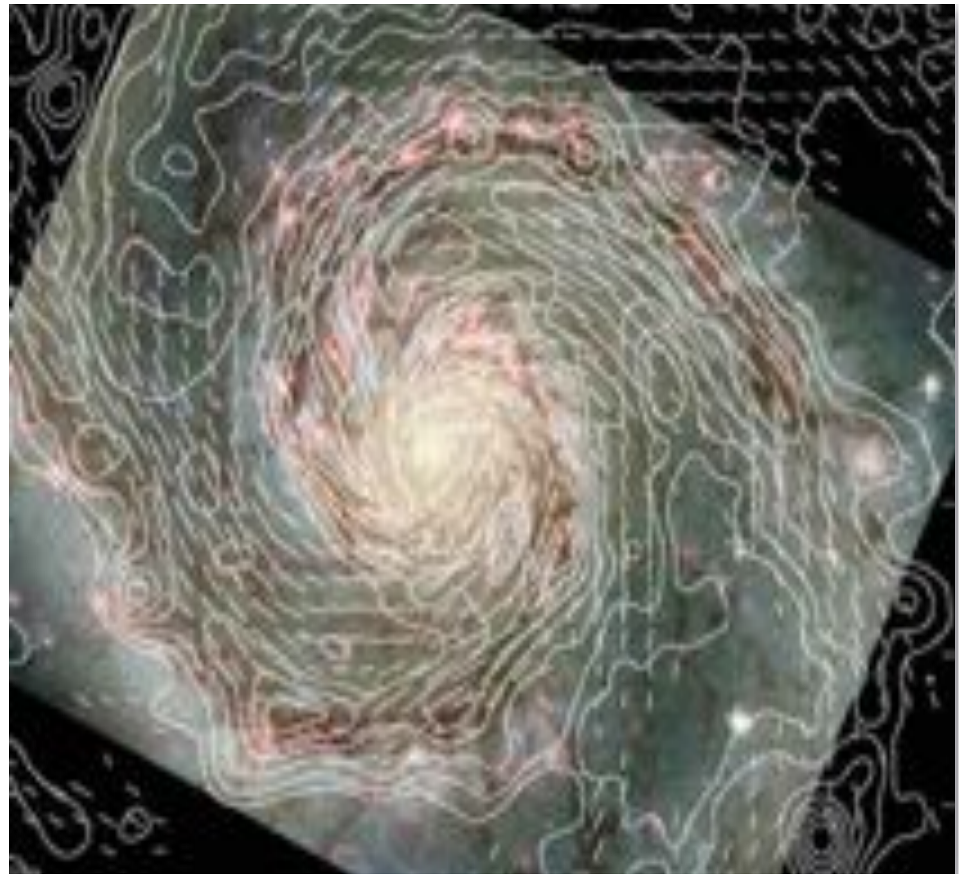
The Radio sky is generally quite different from the optical sky:
=> most of the radio sources are located at cosmological distances!

Radio sky surveys also show a large excess in the faint radio source counts - the first evidence of rapid cosmic evolution (1960).

The NRAO 5GHz sky survey projected on the sky around Greenbank, USA.

What else makes radio astronomy “special” - 2

Radio polarisation measurements (via Faraday rotation) are just about the only way astronomers have of measuring magnetic fields in galaxies.



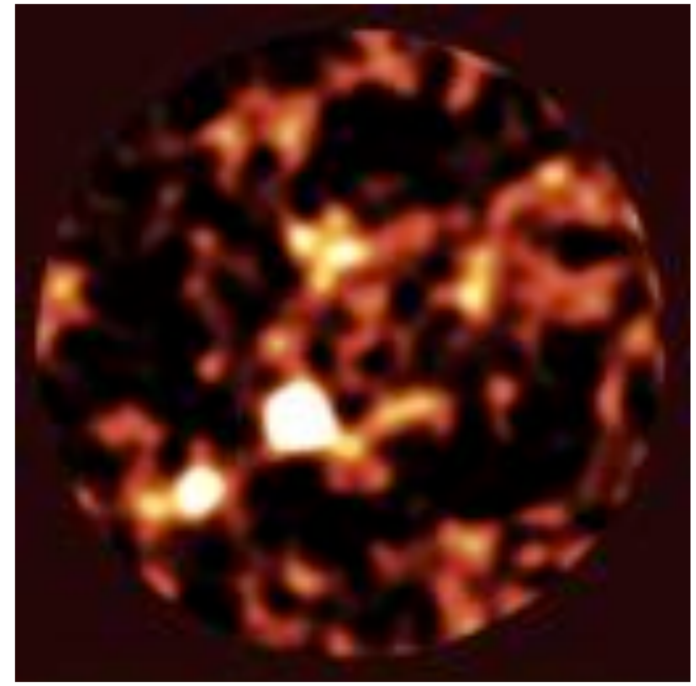
Non-thermal nature of radio emission: probes the violent, high energy, Universe.

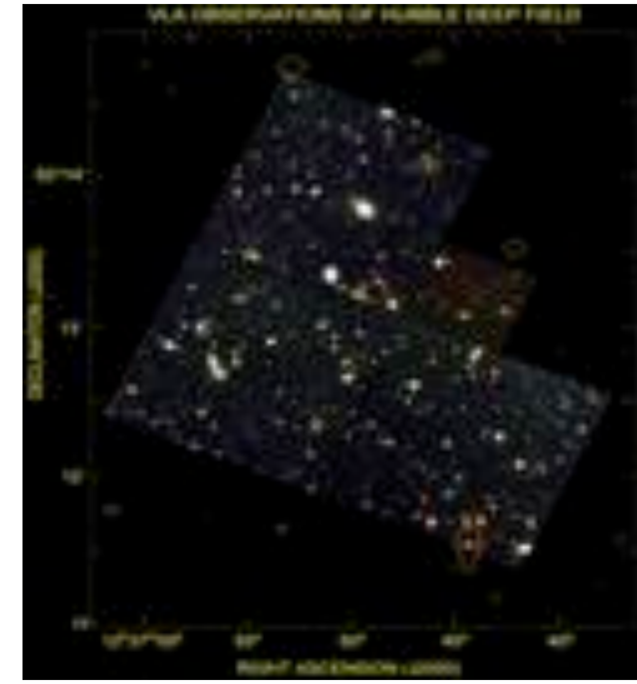
Much of the radio universe is powered by *gravitation* (massive and super-massive black holes), rather than nuclear fusion.

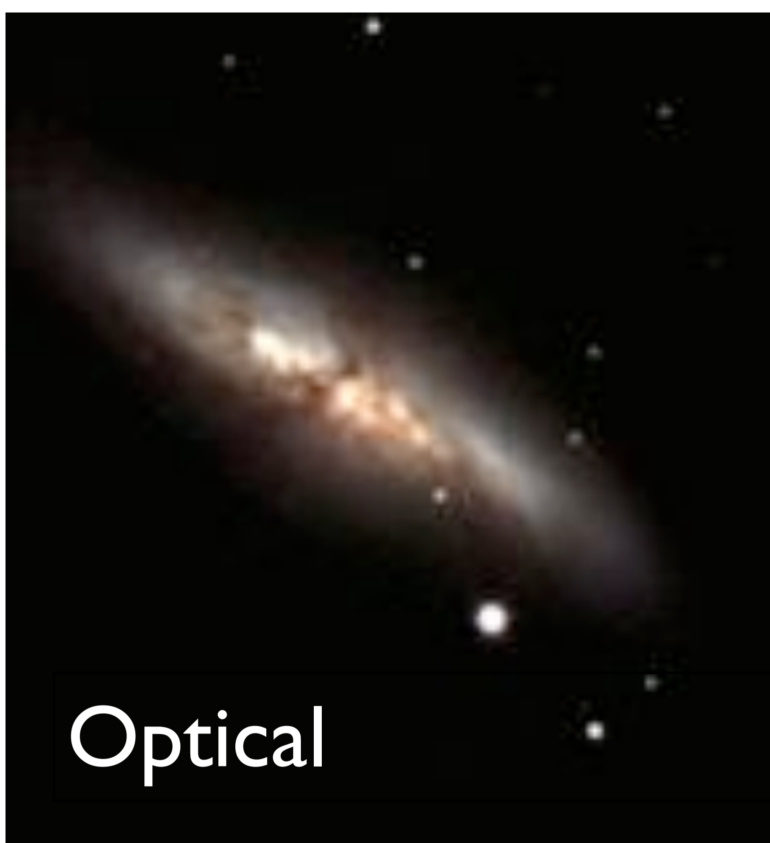
What else makes radio astronomy "special" - 3

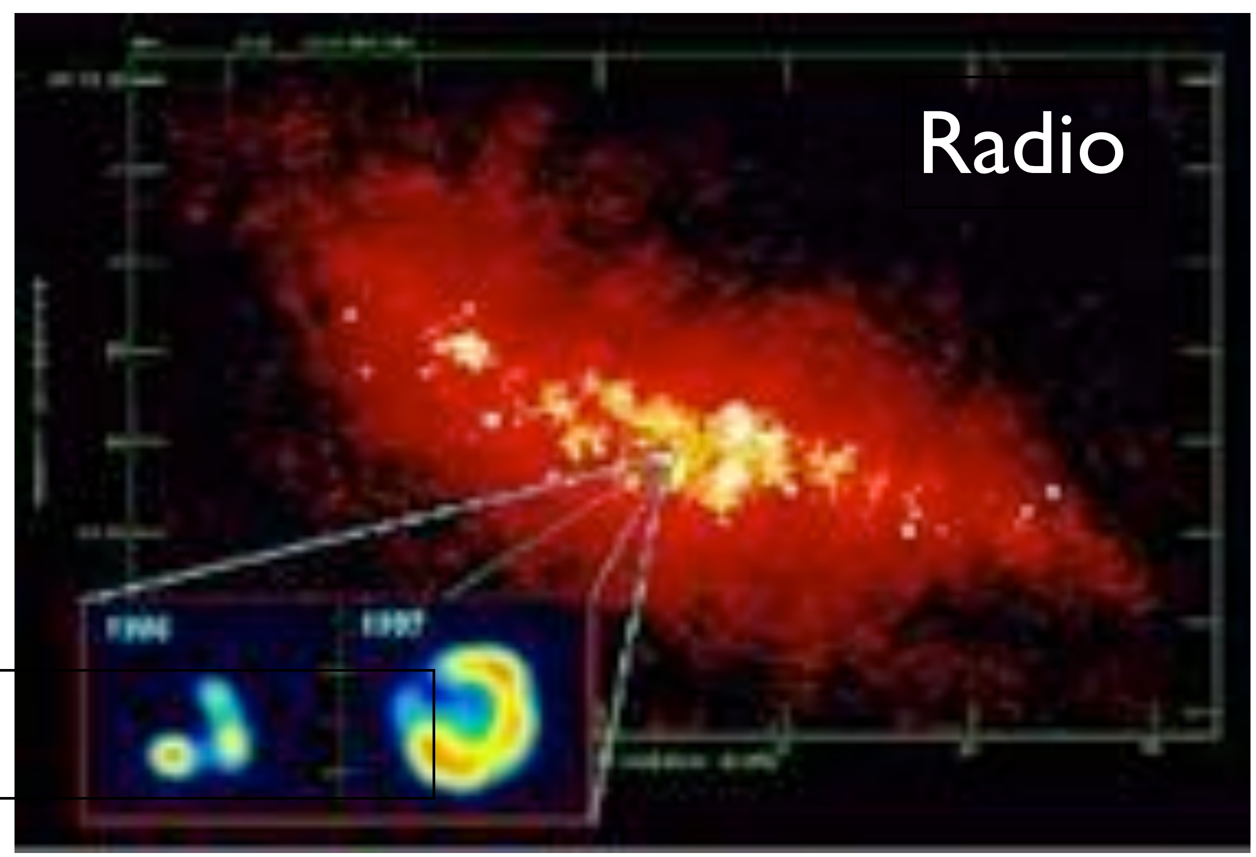
Radio waves (including sub-mm) are largely unaffected by dust - can detect highly obscured star-forming systems at high redshift.

A good example is the Hubble Deep Field. Most of the sub-mm sources detected by the JCMT (SCUBA) have no optical counter-parts - even in the deepest images.





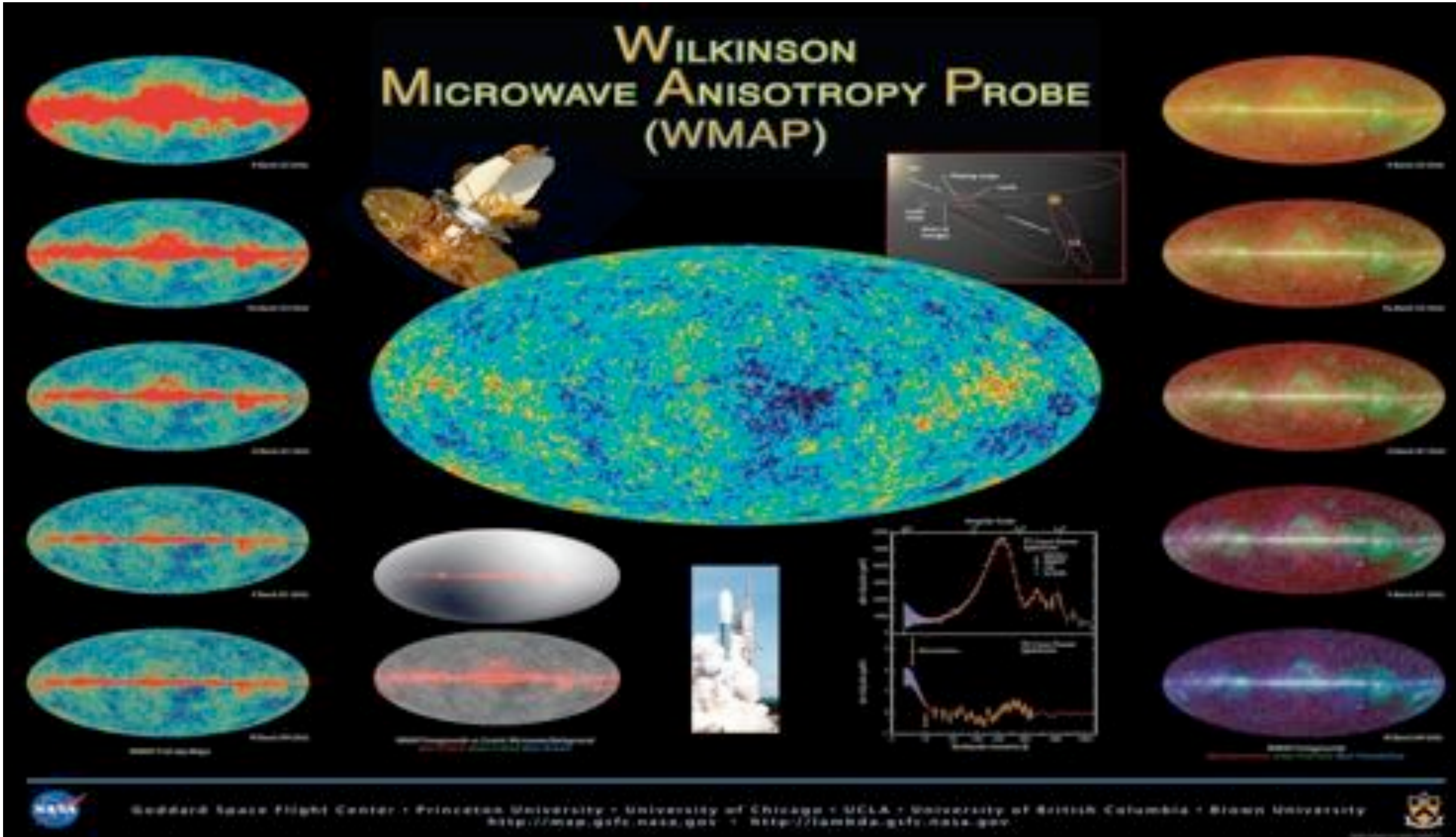




Interacting galaxies like M82 are forming stars at rates which are 10x greater than our own Milky Way. Completely obscured at optical wavelengths, radio observations reveal a swathe of supernovae in the inner nuclear region

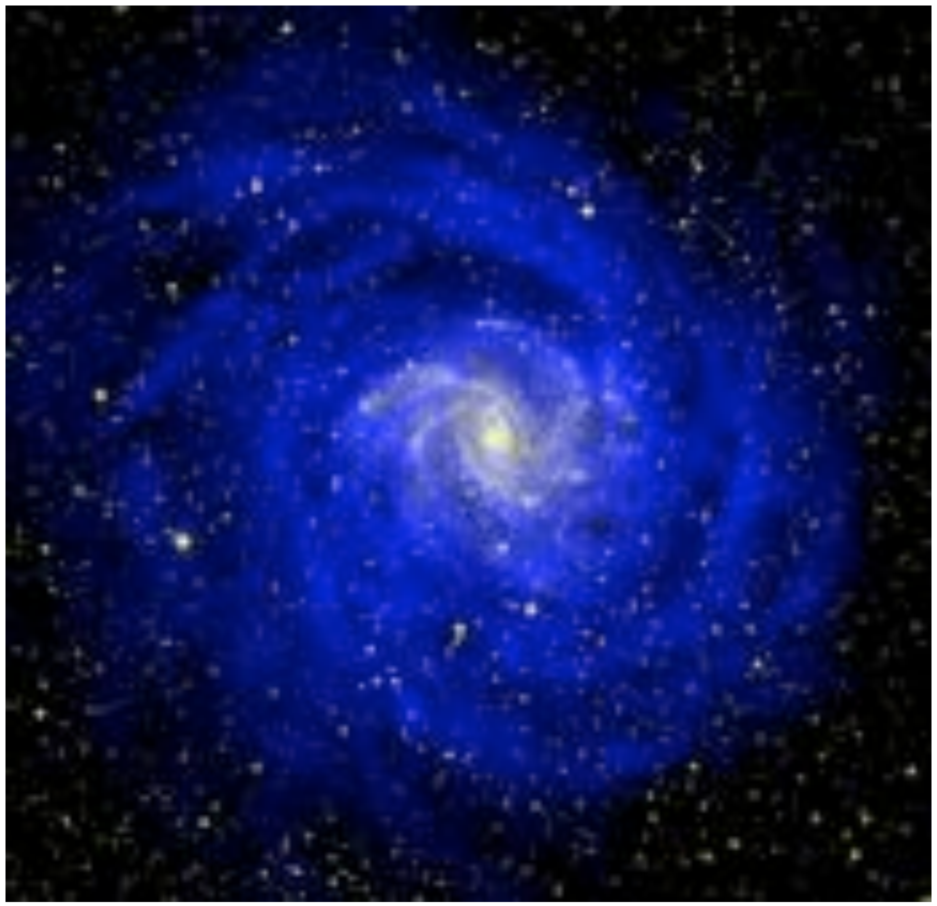
What else makes radio astronomy “special” - 4

Radio waves at mm wavelengths measure fluctuations in the temperature of the photons that escaped from the last scattering surface (z ~ 1000), when the Universe became neutral. The power spectrum of the signal can be used to determine the main cosmological parameters.

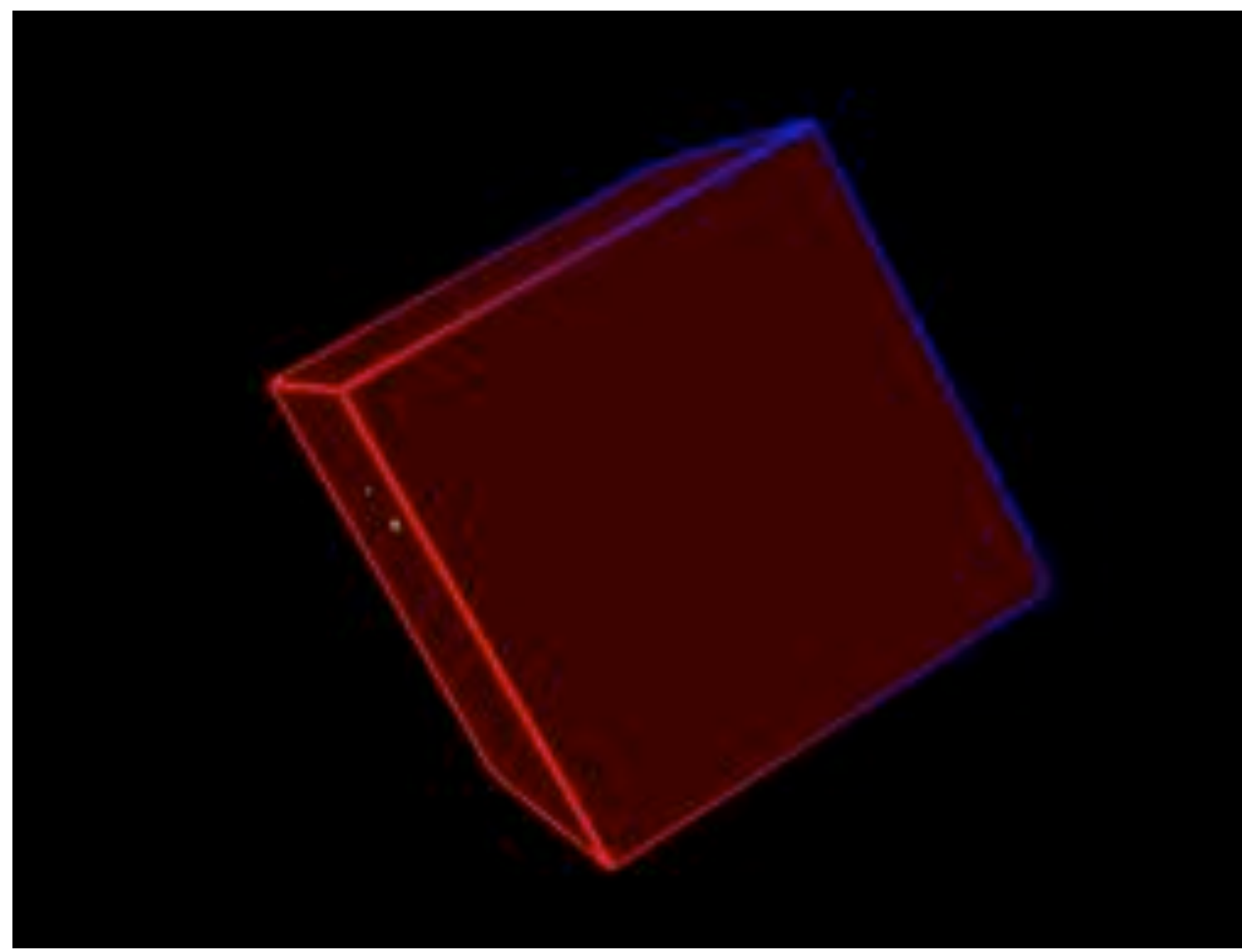


What else makes radio astronomy "special" - 5

Neutral Hydrogen of course...



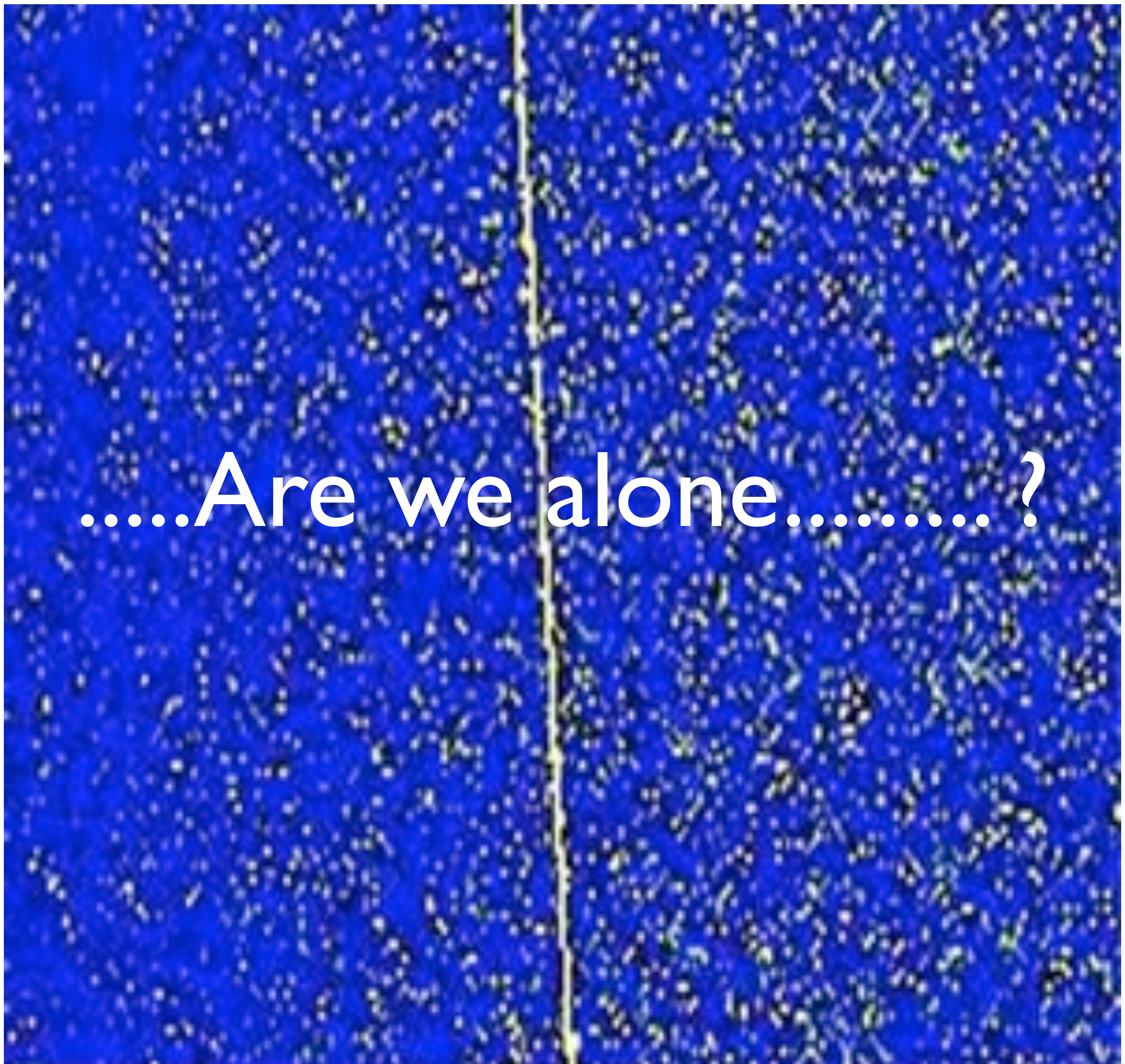
.....Near



And far.....

What else makes radio astronomy “special” - 6

SETI... future radio telescopes may at last provide the answer to the ultimate question...



Lecture 2(of 28)

Radio telescopes - antennas, dishes and performance

Lecture overview

Basic terms in radio astronomy - Flux density, intensity, brightness temperature

Tools of the trade: Fourier Transforms, decibels etc.

Radio telescope systems:

- antennas (simple dipoles)
- paraboloid reflectors, sub-reflectors
- other reflectors types
- telescope performance (surface accuracy, pointing, gain)
- receiver feed horns, frequency flexibility

Basic terms and formulae

- Properties of "black-body radiation" (you should all be familiar with this!)
  - functional form is called the "Planck function":

$$B_\nu(T) = \frac{2h\nu^3/c^2}{e^{h\nu/kT} - 1} \quad (1)$$

Units of spectral energy density are Watts per Hz per sq. metre per steradian

19th cent. physicist studies impirically the intensity pk wavelength prop T;

int prop T^4.

log-log plot B vs v shows slope +2

optically thick part of the spectrum

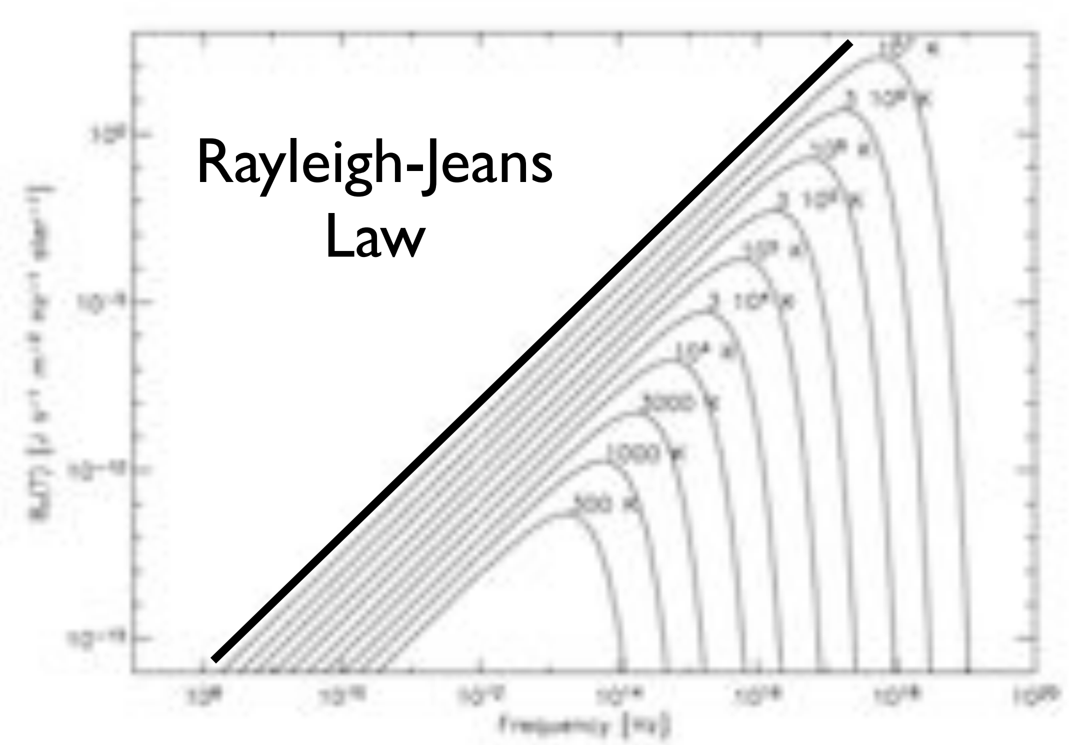
Radio photons are pretty wimpy: $h\nu/kT << 1$ $\quad e^{h\nu/kT} \sim 1 + h\nu/kT + ...$

$$\Longrightarrow B_\nu(T) = 2kT\nu^2/c^2 \quad (2)$$

- Eqn(2) is known as the Raleigh-Jeans law i.e. at low frequencies the intensity increases with the square of the frequency.

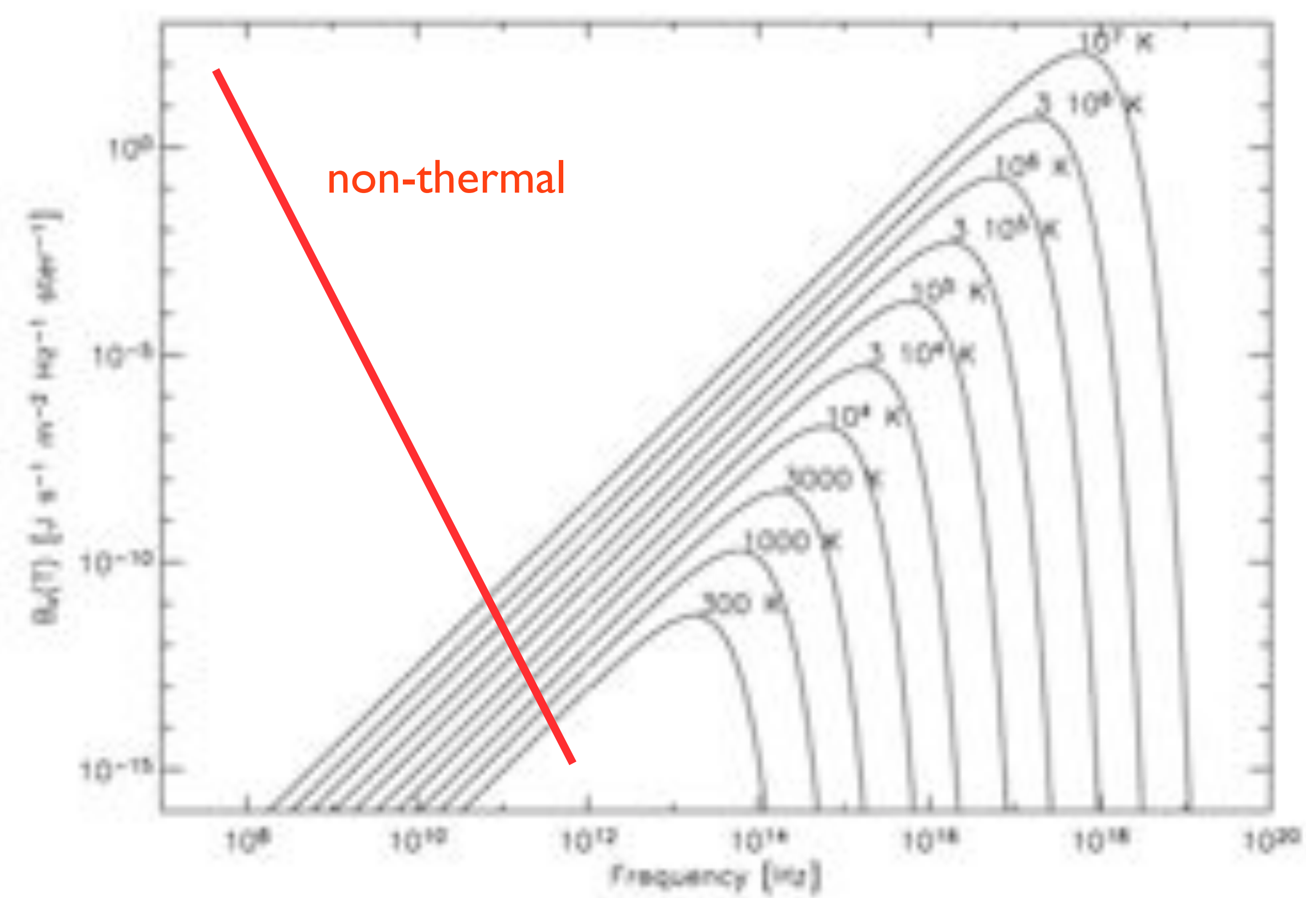
  Note that the R-J law holds all the way through the radio regime for any reasonable temperature

  k is boltzmann's constant = 1.38E-23 $m^2\ kg\ s^{-2}\ K^{-1}$



In the Raleigh-Jeans limit, a black body has a temperature given as (2): $T = B_\nu(T)c^2/2k\nu^2$

Radiation mechanisms in radio astronomy are often non-thermal (Reber's discovery):



But this does not stop radio astronomers also talking about the "brightness temperature" of a source: i.e. the equivalent or effective temperature that a blackbody would need to have in order to be that bright!

$$T_b = B_\nu(T)c^2/2k\nu^2$$

e.g. for Cyg-A, high resolution (small solid angle) VLBI observations measure T_b ~ 100E6 Kelvin - this is not a physical temperature but a measure of the energy density of the electrons and magnetic fields that generate radio emission via non-thermal emission mechanisms (synchrotron).

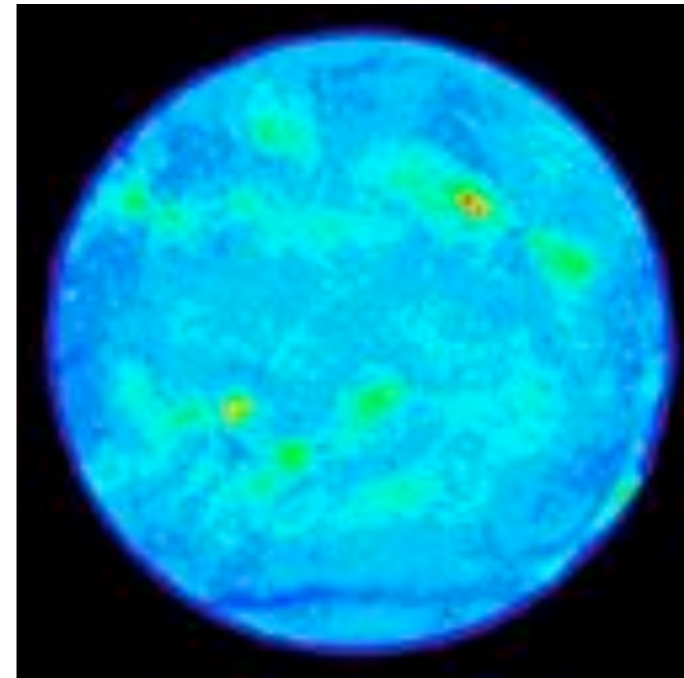
More examples of brightness temperatures:

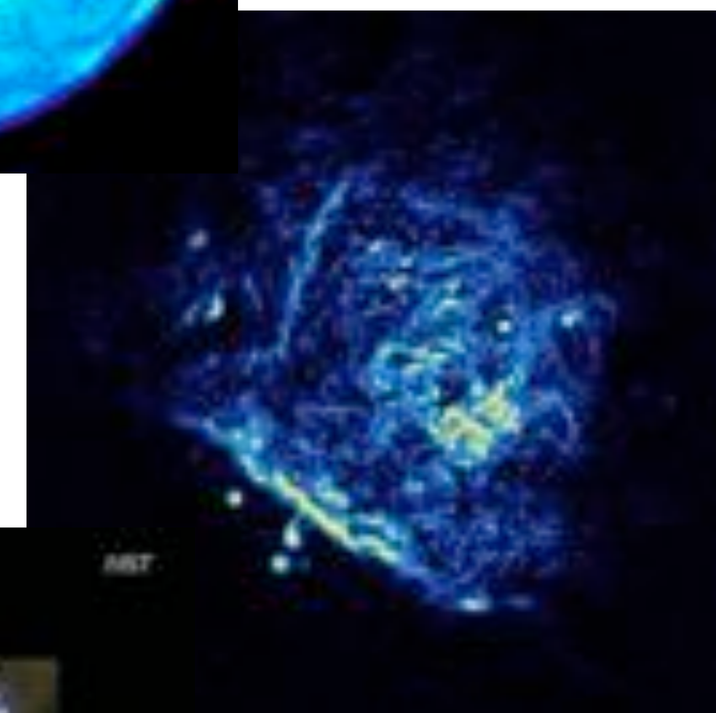
“Blank” sky ~ 2.73 K (big bang BB radiation)

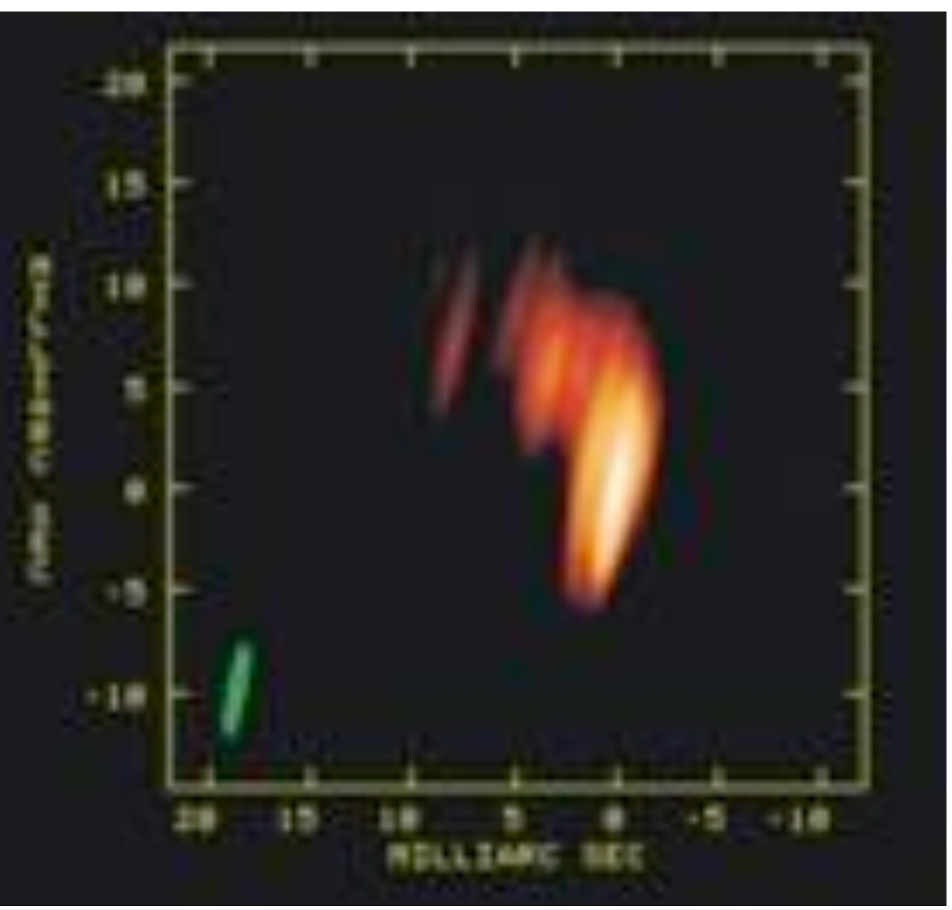
Sun at 300 MHz, 500000 K

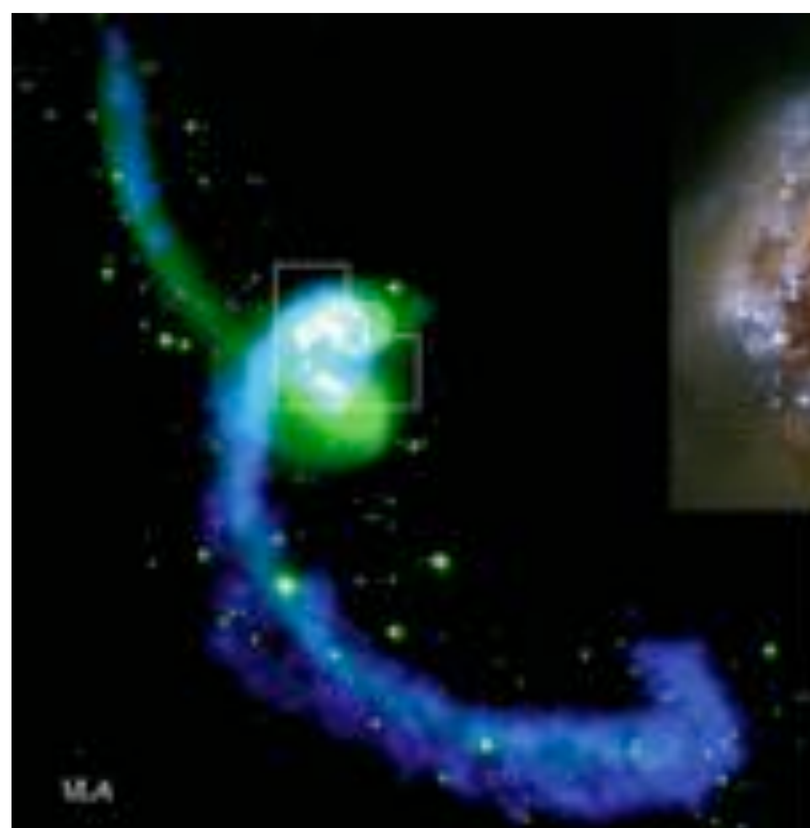
Orion Nebula at 300 GHz ~ 10-100 K (“warm” molecular clouds)

Quasars at 5 GHz ~ 10^{12} K (synchrotron)







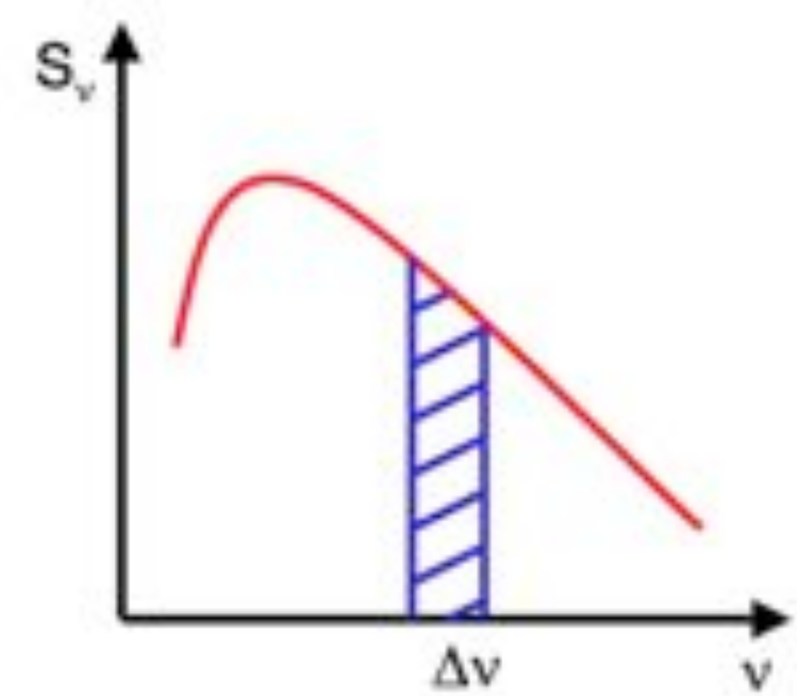


Radio telescopes/astronomers most often measure the (Spectral) "Flux Density" of a source.

The Flux density (S), is the power received (P) within a certain frequency band (dv), via a certain effective collecting area (A) with efficiency η :

$$S = 2\frac{P}{\eta A d\nu}$$ (Watts m^{-2} Hz^{-1}) [3]

The factor of 2 above is because the measurement of power is traditionally only made via one polarisation channel, and it is assumed that the other hand will contribute the same amount of power.

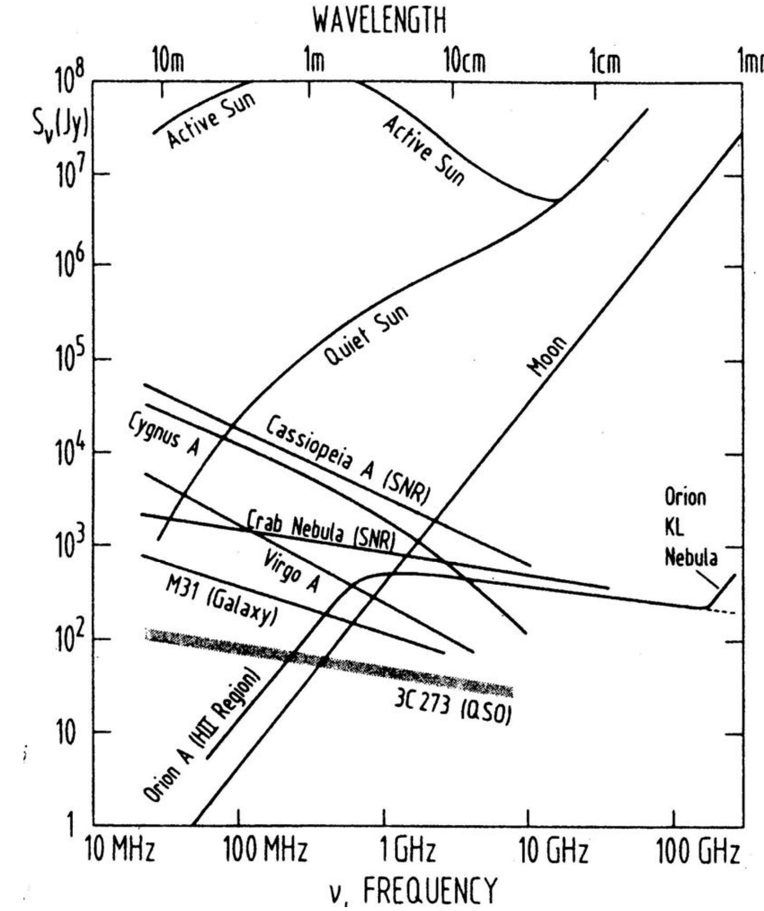


The unit of Flux density is the Jansky (Jy): 1 Jy = 10^{-26} Watts m^{-2} Hz^{-1}. Typical units include milliJansky (mJy) and microJy (uJy). NanoJy requires SKA!

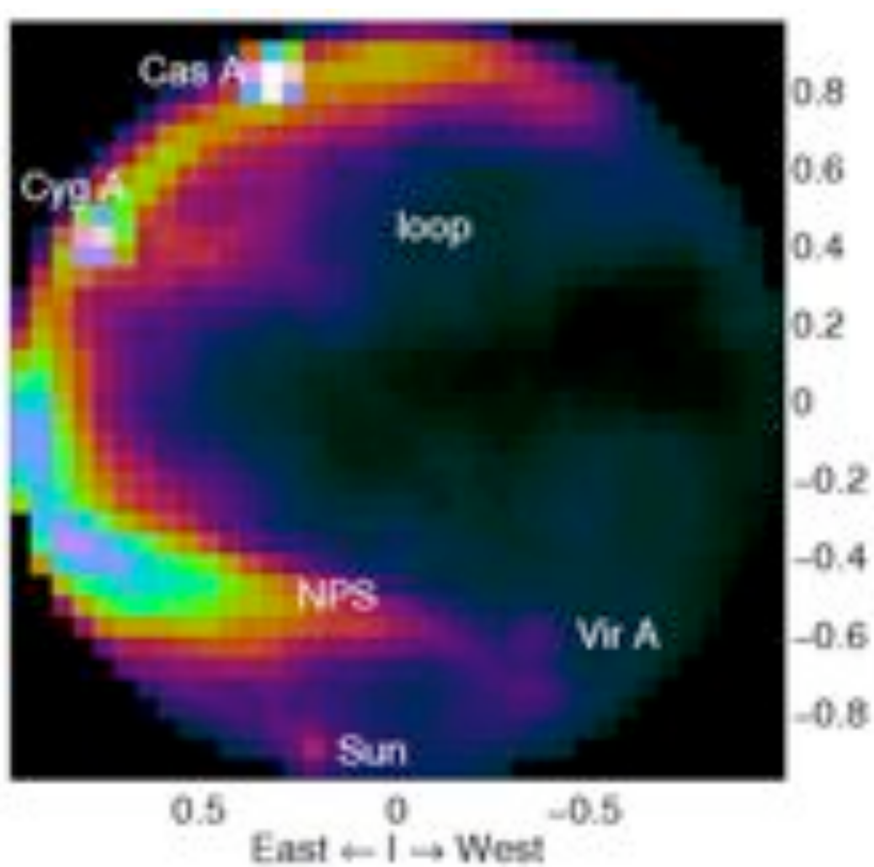
Since the Flux density is proportional to the distance, d^{-2}, between the observer-source, it is not an intrinsic property of the source i.e. it does not reflect the real source luminosity e.g. quiet sun has a flux density of 1000 Jy at 6cm.

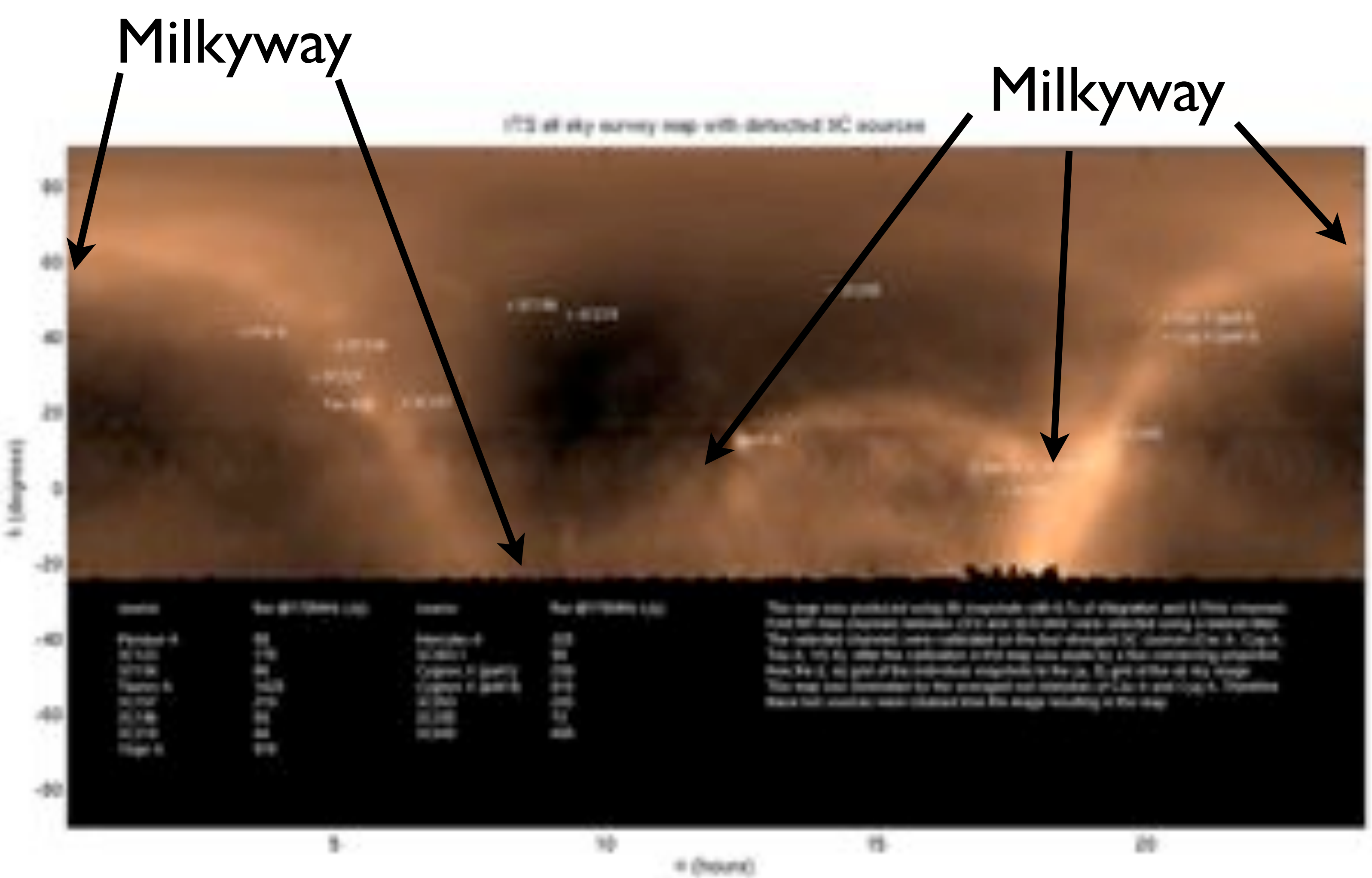
The dominant sources seen in the radio sky are the Sun, supernova remnants, radio galaxies, the Milkyway. The quiet Sun has a typical flux density of 10^5 Jy while the next strongest sources are the radio galaxy Cygnus-A (Cyg-A) and the supernova remnant Cassiopeia-A (Cas-A), both of which have flux densities of 10E4 Jy.

e.g. sources as bright as 1 Jy are relatively rare. For a Westerbork antenna D ~ 25 metres; efficiency ~ 0.7 (==> effective collecting Area ~ 340 sq metres); observing bandwidth 20 MHz. A source of 1 Jy produces a signal of only ~ 7E-17 Watts!



LOFAR images of whole sky (Wijnholds et al.):





The Flux Density is equal to the Planck function, "specific intensity" I(v), integrated over solid angle:

$$S = \int I(\nu) d\Omega \qquad (\text{units}: \text{Wm}^{-2}\text{Hz}^{-1}) \qquad [4]$$

$$S = \int 2kT_b\nu^2/c^2 d\Omega = 2k\nu^2/c^2 \int T_b d\Omega \qquad [5]$$

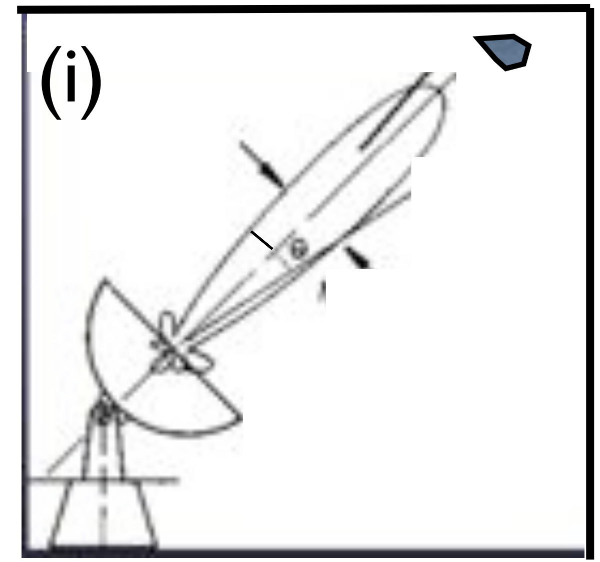
i.e. the Flux density is just the brightness temperature integrated over the source.

Astronomers usually measure Flux Density in Jansky (Jy):

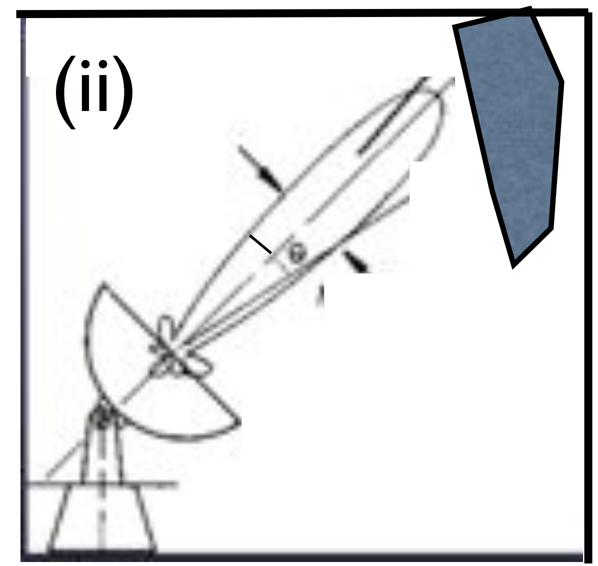
1 Jy = 10^{-26} Watts m^{-2} Hz^{-1}

When measuring the Flux density of a radio source there are two likely cases:

(i) the telescope observes a radio source that is smaller or the same size as the telescope beam, $\theta \sim \lambda/D$



(ii) the telescope observes a radio source that is larger than the telescope beam.



In case (i) the telescope measures all of the source and the measured flux density, S, is measured by integrating the intensity over the solid angle subtended by the source.

In case (ii) part of the source falls outside of the telescope beam - in this case the measured flux density, S', is measured by integrating the intensity over the telescope beam. Clearly, the measured flux density (S') in this case, is less than the total flux density of the source:

$$S' = (2kT/\lambda^2)\, \Omega_a = 2kT/D^2 \quad [6a]$$ where Ω_a is the solid angle of the beam < Ω_{source}.

N.B. this means that a larger telescope will actually measure a smaller flux density for this resolved radio source. Surface brightness units often used in radio maps or images of a radio source are in "Jy per beam".

Just a re-cap on the various terms:

I_ν (also written as B_ν) = specific intensity = surface brightness (Watts/Hz/m^2/sr)

S = Flux density (Watts/Hz/m^2) $$S = \int I_\nu d\Omega$$

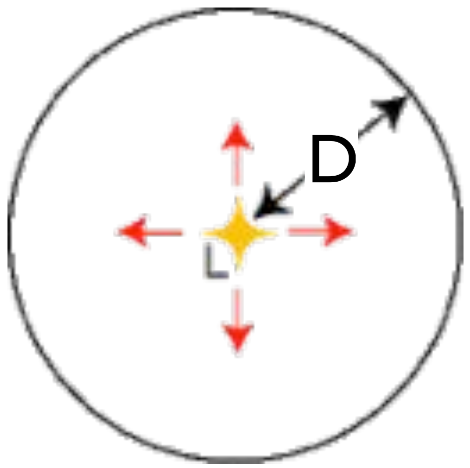
P = Power received/measured (Watts) $$P = A_{tel} \int I_\nu d\Omega d\nu$$

Other terms you need to know:

F = Flux (Watts/m^2) $$F = \int I_\nu d\Omega d\nu$$

L = Luminosity; L = F x $4\pi D^2$

Note L is a property intrinsic to the source



Star radiating luminosity L into a sphere of radius D

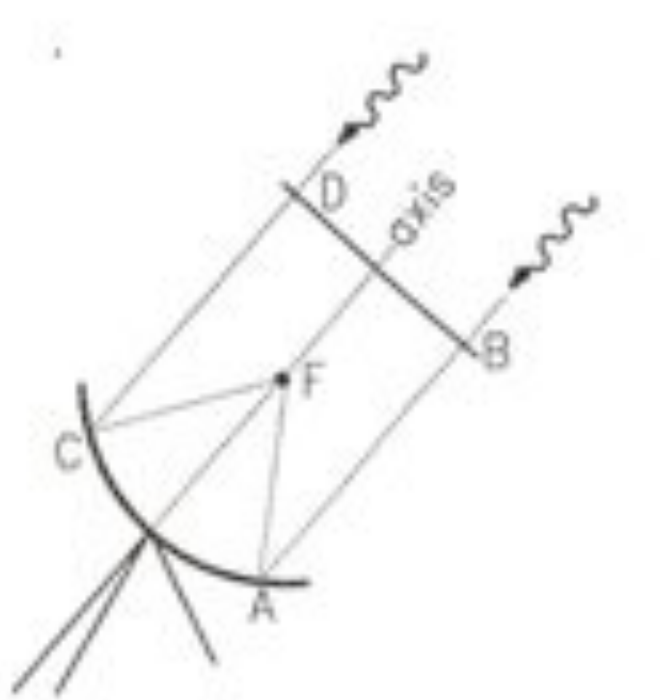
Radio Telescopes (Antennas)

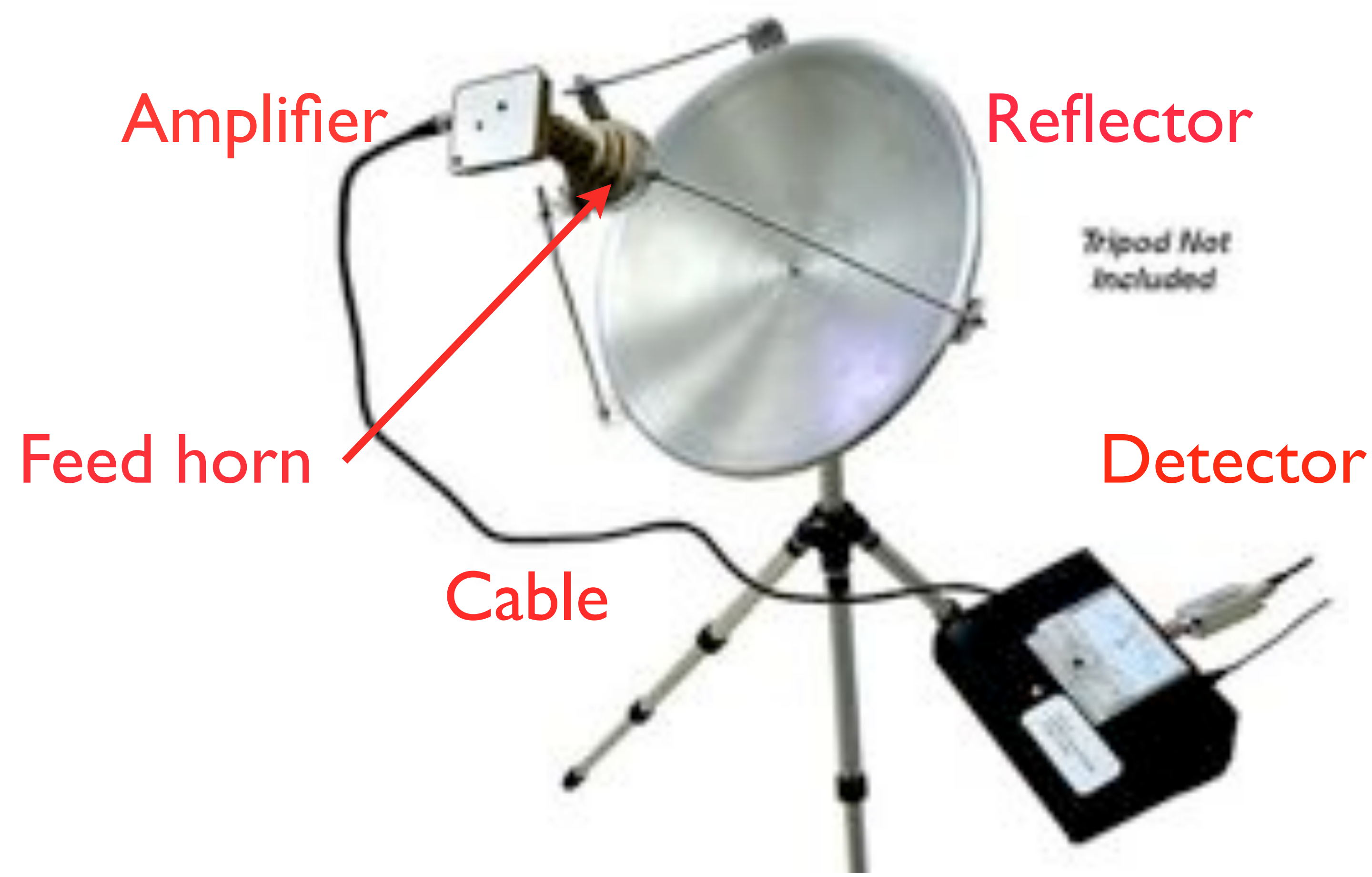
Radio photons are too wimpy to do very much - we cannot usually detect individual photons

- e.g. optical photons of 600 nanometre => 2 eV or 20000 Kelvin (hν/kT)
- e.g. radio photons of 1 metre => 0.000001 eV or 0.012 Kelvin

➡ Photon counting in the radio is not usually an option, we must think classically in terms of measuring the source electric field etc.

i.e. the best we can do is for the incoming EM-wave electric field oscillations to induce voltage oscillations in a conductor.

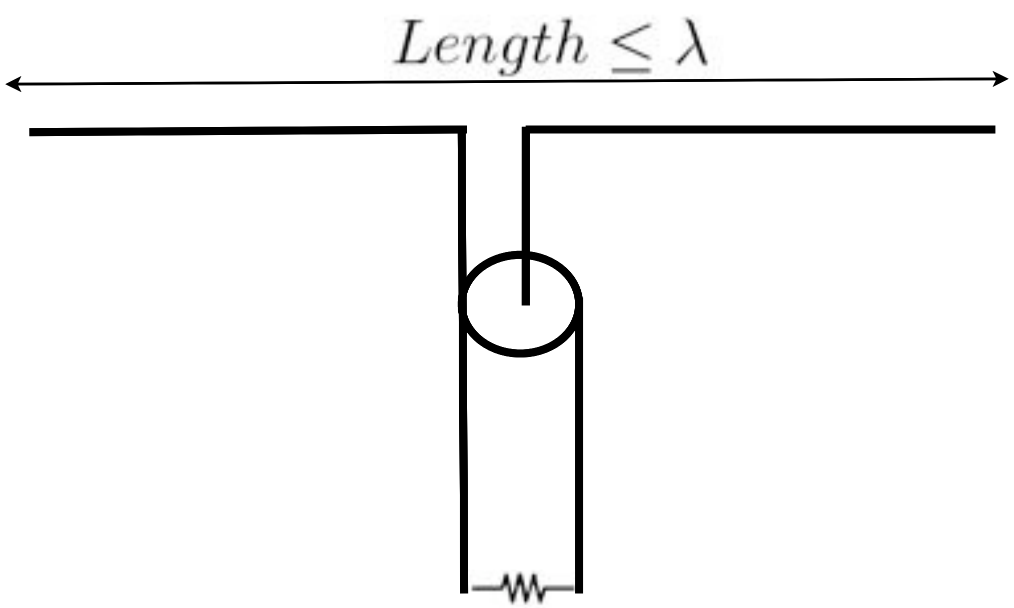




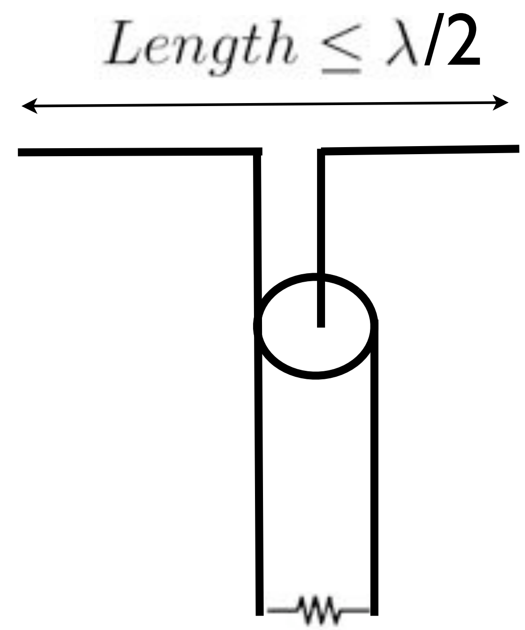
Types of antenna or antenna arrays:

Wavelength > ~1 metre: simple wire antennas can be used...

Dipole

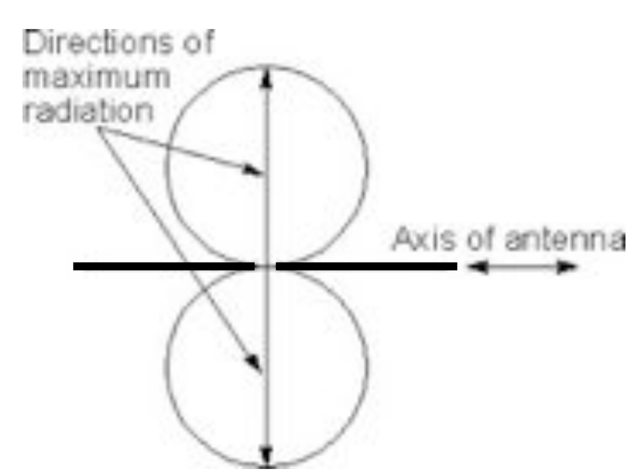


half-wave dipole

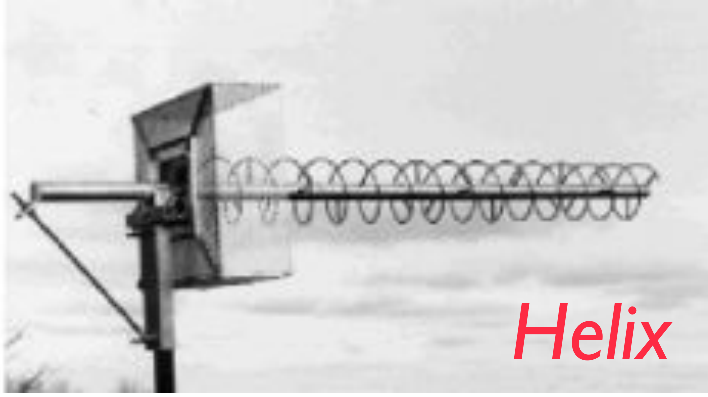


E-field of incoming radiation sets up currents in the antenna ==> voltages can be measured across a resistor. Dipole length must be kept short, $Length \leq \lambda$. N.B. any antenna is only sensitive to one polariastion (current is induced by field that is parrallel to dipole length).

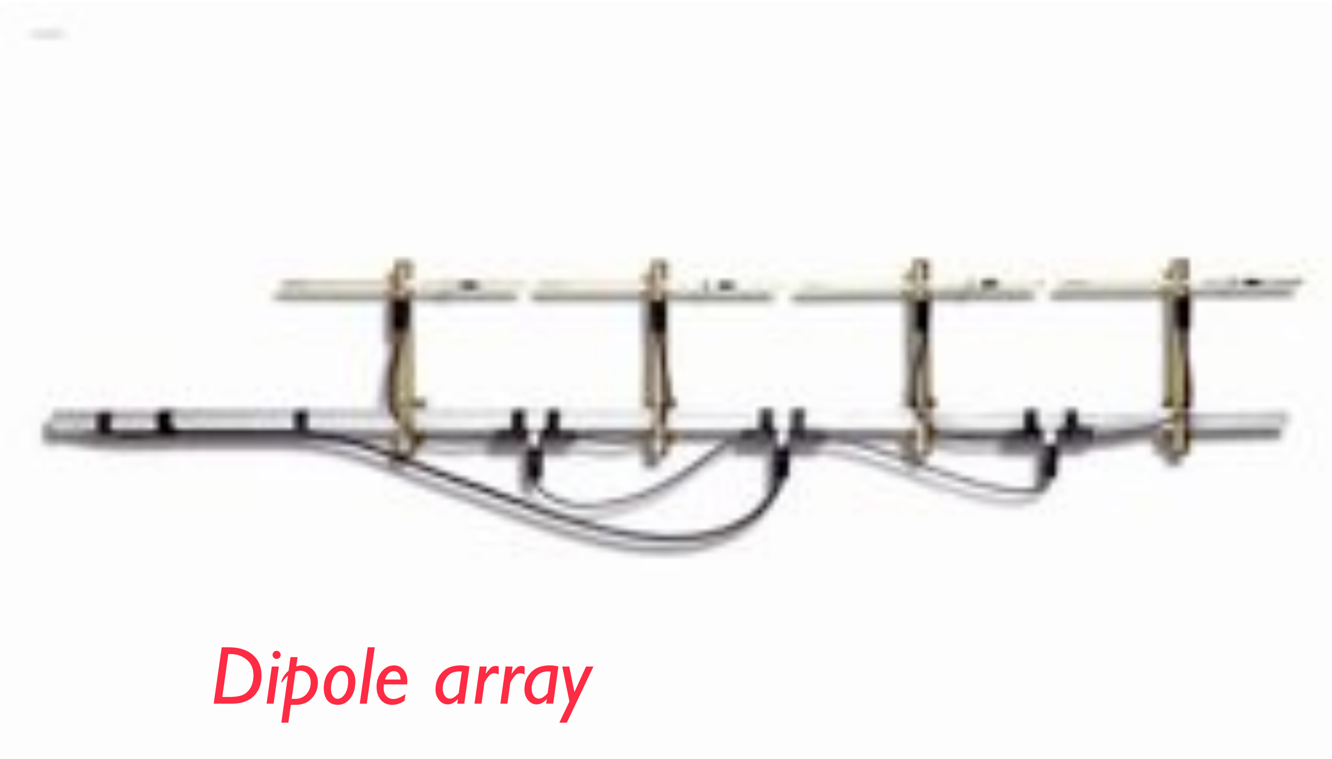
The simplest antenna is the half-wave dipole $Length \sim \lambda/2$. The Directivity (max gain) of a half-wave dipole is measured in dBi, dB above an isotropic (non-directional) radiator. For a dipole G ~ 1.6 dbi (not much better than isotropic!). The gain can be improved by combining together the output of several dipoles arranged in an array.



Effective area can also be increased by (for example) using a Yagi antenna. Parasitic antennas direct the wave towards the dipole. Log-periodic antennas are suitable as receptors of broad-band signals.



The gain of a single dipole can be greatly improved by combining together the output of many dipoles arranged in an array (right):



S. Jocelyn Bell Burnell was born in northern Ireland in 1943. After receiving a B.S. degree in physics from Glasgow University, Scotland, she went to Cambridge University, England, where she earned her doctorate in radio astronomy in 1969. Since then she has done research in the newest branches of astronomy involving gamma-rays and x-rays. In 1978 she received the American Tentative Society Award for her pulsar research. Currently she is a research scientist at the Mullard Space Science Laboratory of the University College London.

The first Pulsars were detected using huge arrays of dipoles. This concept is similar at some level to what LOFAR uses some 40 years later.

Burnell

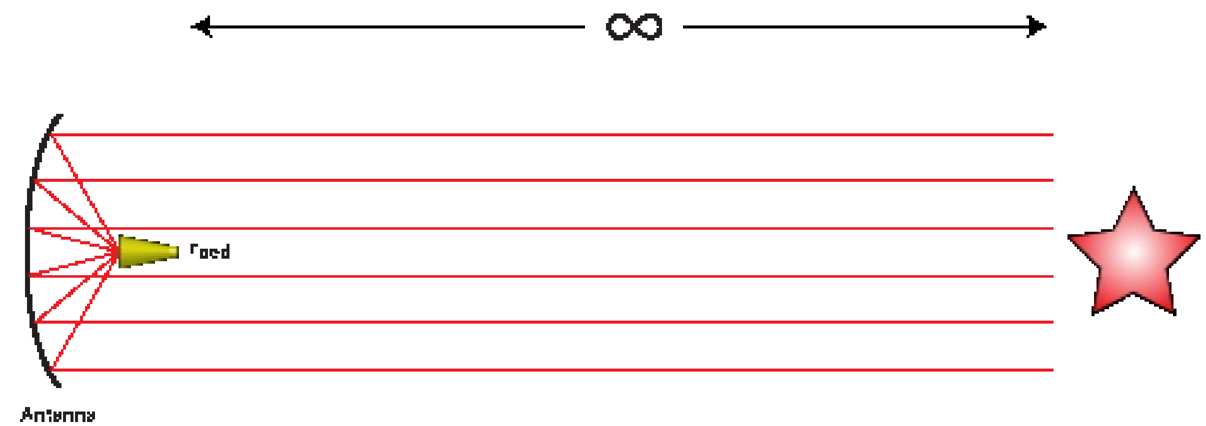
"We put up over a thousand posts and strung more than 2000 dipoles between them."

Dame Jocelyn Bell-Burnell opening LOFAR-UK station

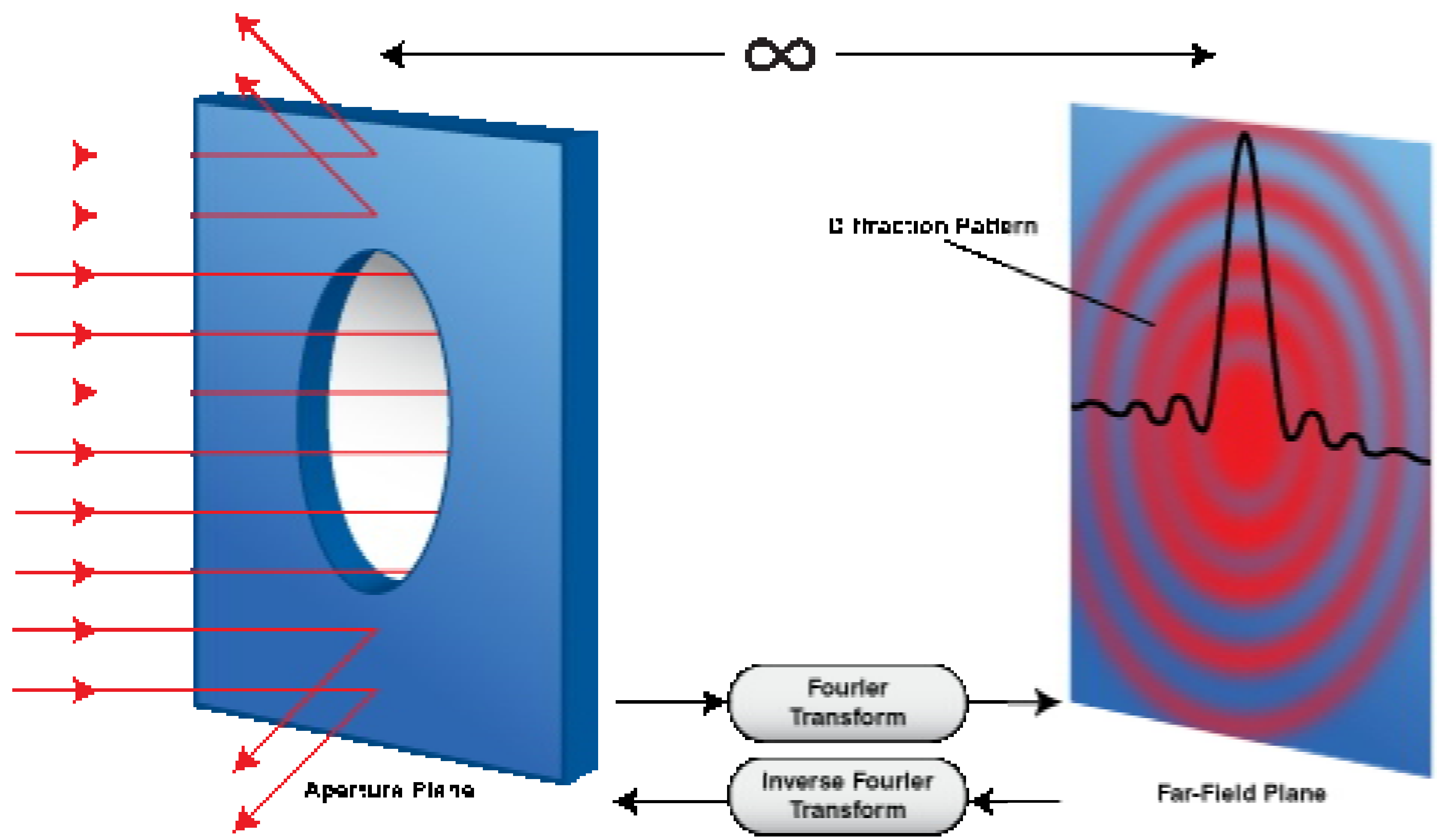
When considering the properties of an radio astronomy antenna its often useful to think in terms of it transmitting (rather than receiving).

Two theorems...

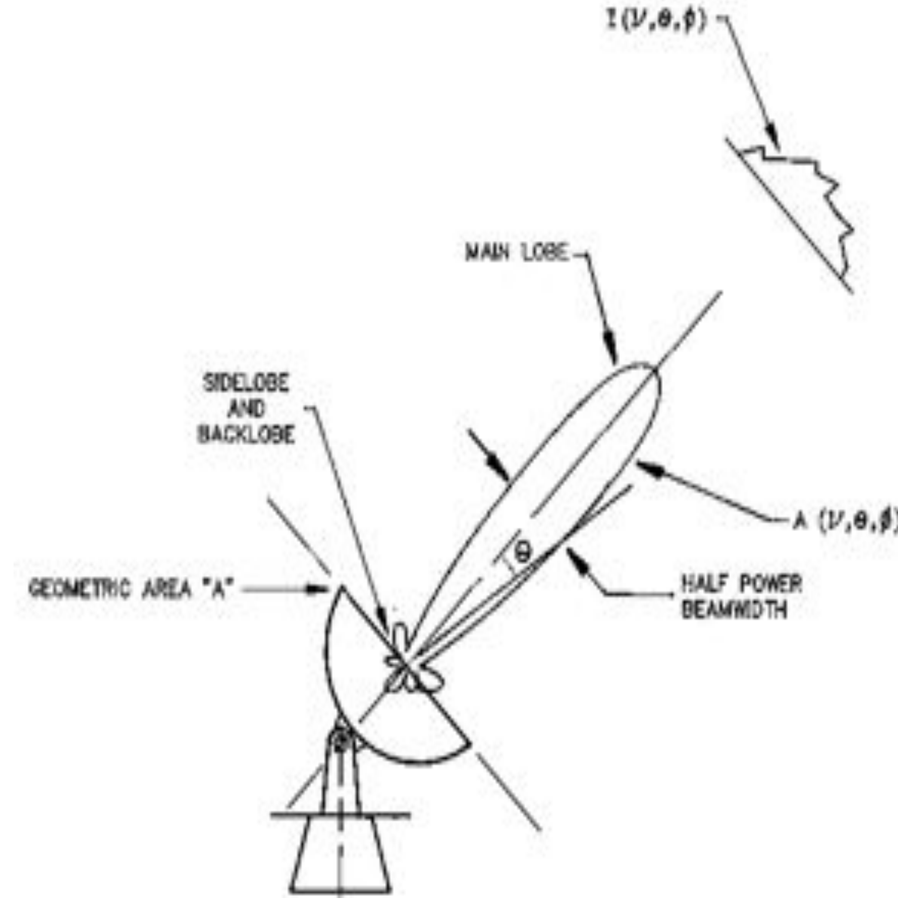
- Reciprocity theorem: Performance of an antenna when collecting radiation form a point source at infinity may be studied by considering its properties as a *transmitter*:



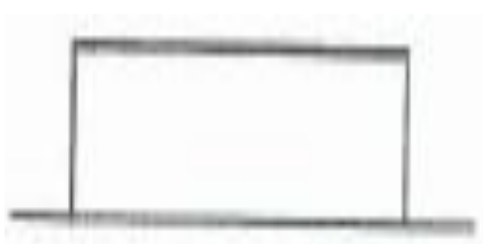
- Far-field pattern (the antenna's "beam") is the Fourier Transform of aperture plane electric field distribution:



The response (voltage beam) of the antenna, B, is the Fourier Transform (FT)of the electric field, E:



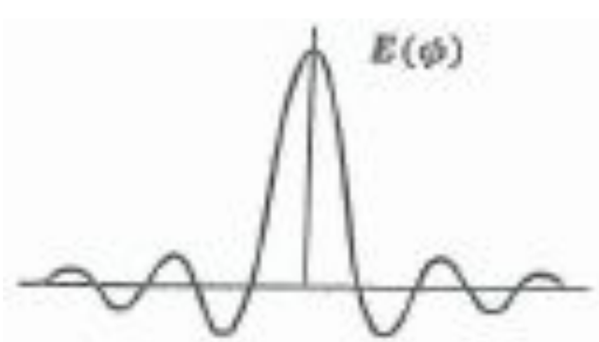
$$B(\theta) = \int E(x) e^{2\pi i x \theta} dx$$



[FT] -->

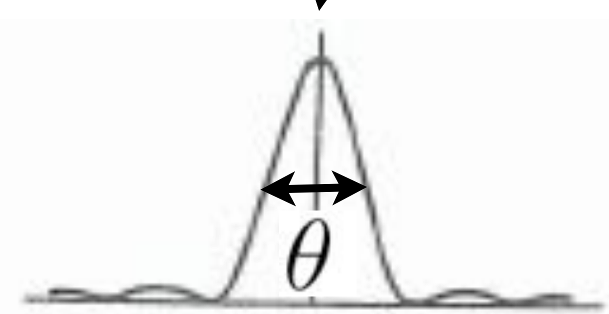
The Power beam $B^2(\theta)$ is the autocorrelation of the E(x):

Main response (lobe)



x

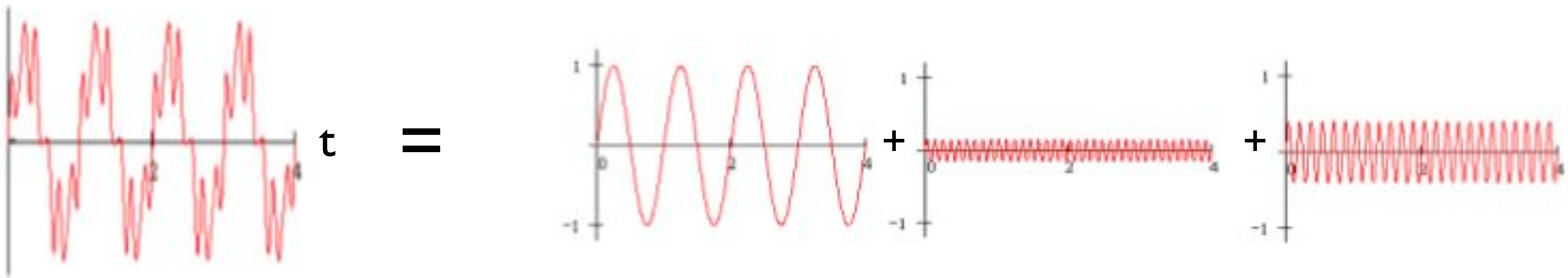
=



FWHM of beam (resolution) is λ/D
D=aperture diameter.

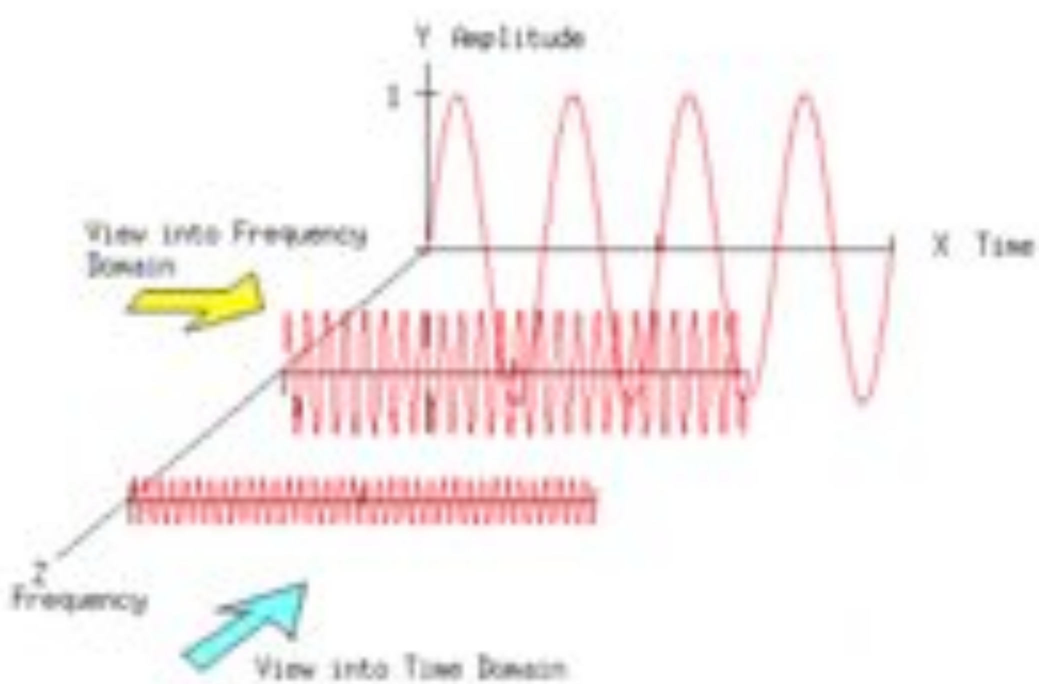
(Unwanted) side-lobes

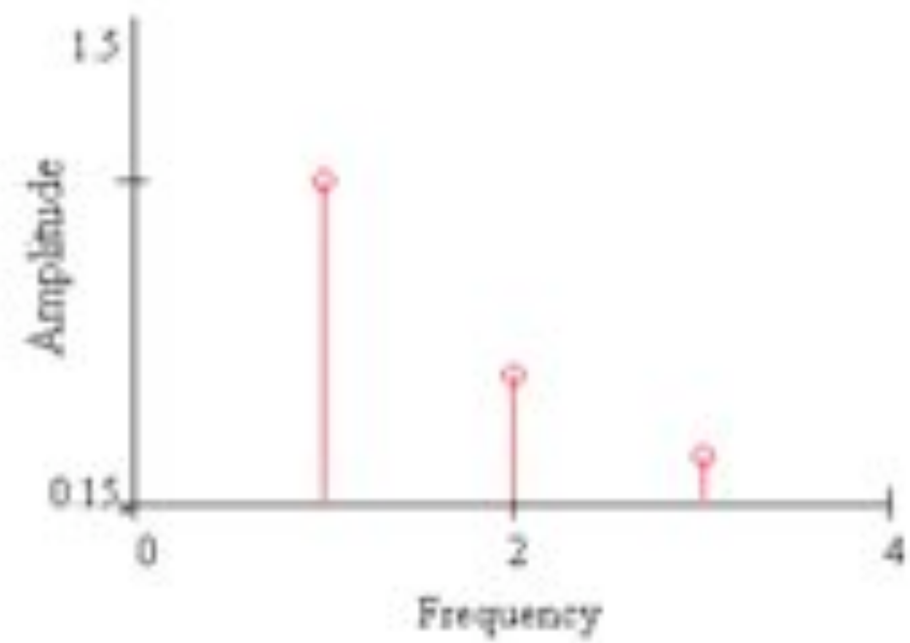
ASIDE: The use of Fourier transforms in radio astronomy is ubiquitous. In the 19th Century, Baron Fourier noticed that its possible to create some very complicated signals by summing up very simple sine and cosine waves of various amplitudes and frequency:



Complex signal *3 simple sine waves added together*

We can also view the same signals in the frequency domain (z-axis):





Most of you will be familiar with FTs from the time domain to the frequency domain:

$$F(\nu) = \int_{-\infty}^{\infty} f(t) e^{-2\pi i \nu t} dt$$ is the Fourier transform of $f(t)$

$$f(t) = \int_{-\infty}^{\infty} F(\nu) e^{2\pi i \nu t} d\nu$$ is the inverse FT of $F(\nu)$

Basically, the idea is that any periodic function can be expressed as the sum of a series of sines and cosines of varying amplitude and phase. In other words, f(t) can be built up from the spectral distribution F(v) which is the power at frequency v.

A good and complete reference is “The Fourier Transform and its applications”, Ronald Bracewell.

The fourier transform of a function e.g. f is often denoted as $\mathscr{F}$(f) and the inverse is $\mathscr{F}^{-1}$ (f).

a function which is *wide* in one domain is *narrow* in the other, and vice-versa:

If $\mathscr{F}$ f(x) = F(s) some basic and general properties of FTs include:

1. $\mathscr{F}$ f(ax) = 1/a F(s/a) - *scaling property of FTs*

2. $\mathscr{F}$ $f(x-x_0) = F(s)e^{i2pi\, x_o S}$ - *shifting property of FTs*

3. Suppose that g(x) = f(x) * h(x), then:

G(s) = F(s) H(s) - *convolution theorem of FTs*

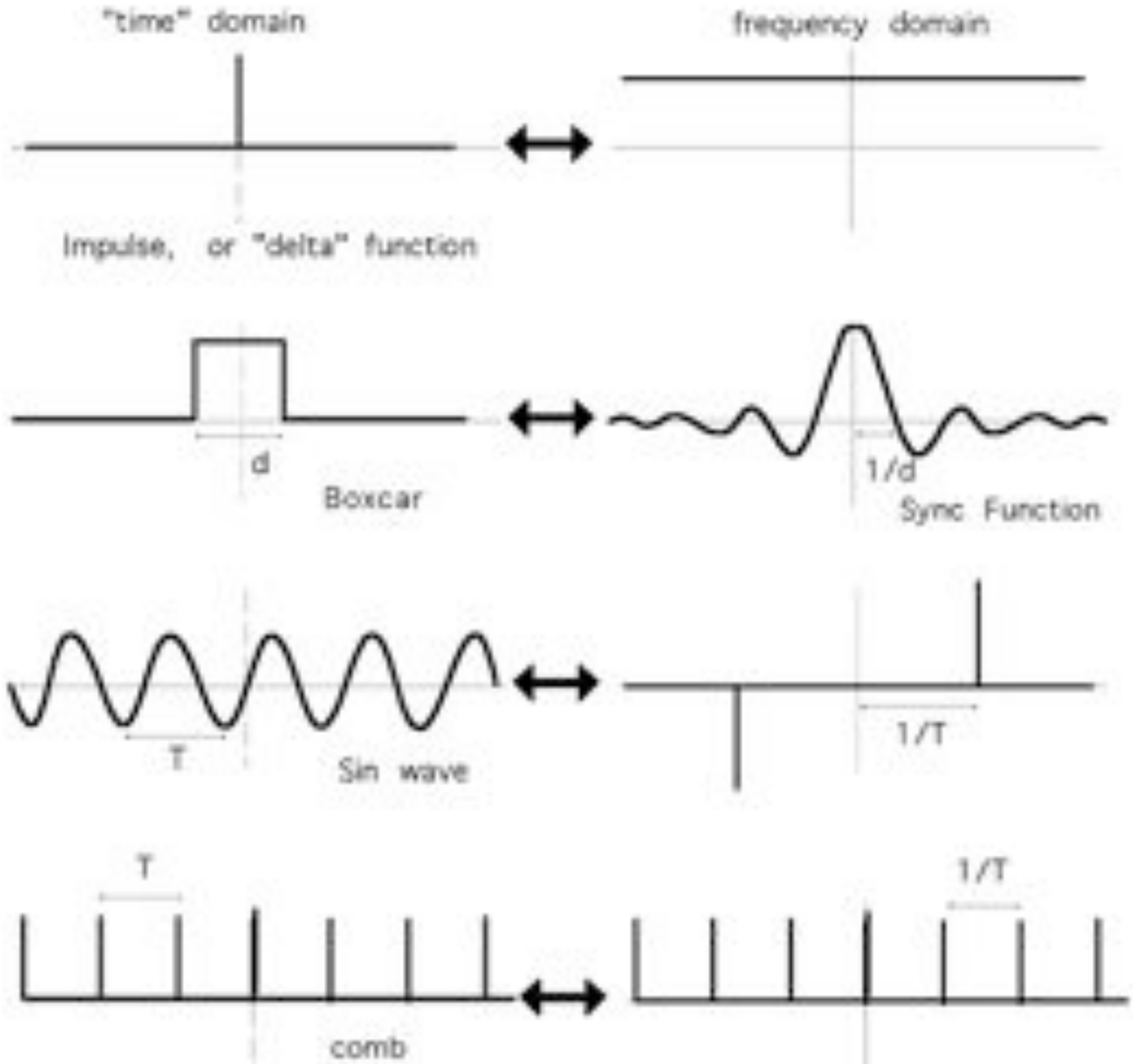
4. Consider the correlation of 2 signals:

$$h(x) = \int_{-\infty}^{\infty} f(u)\, g(x+u)\, du$$

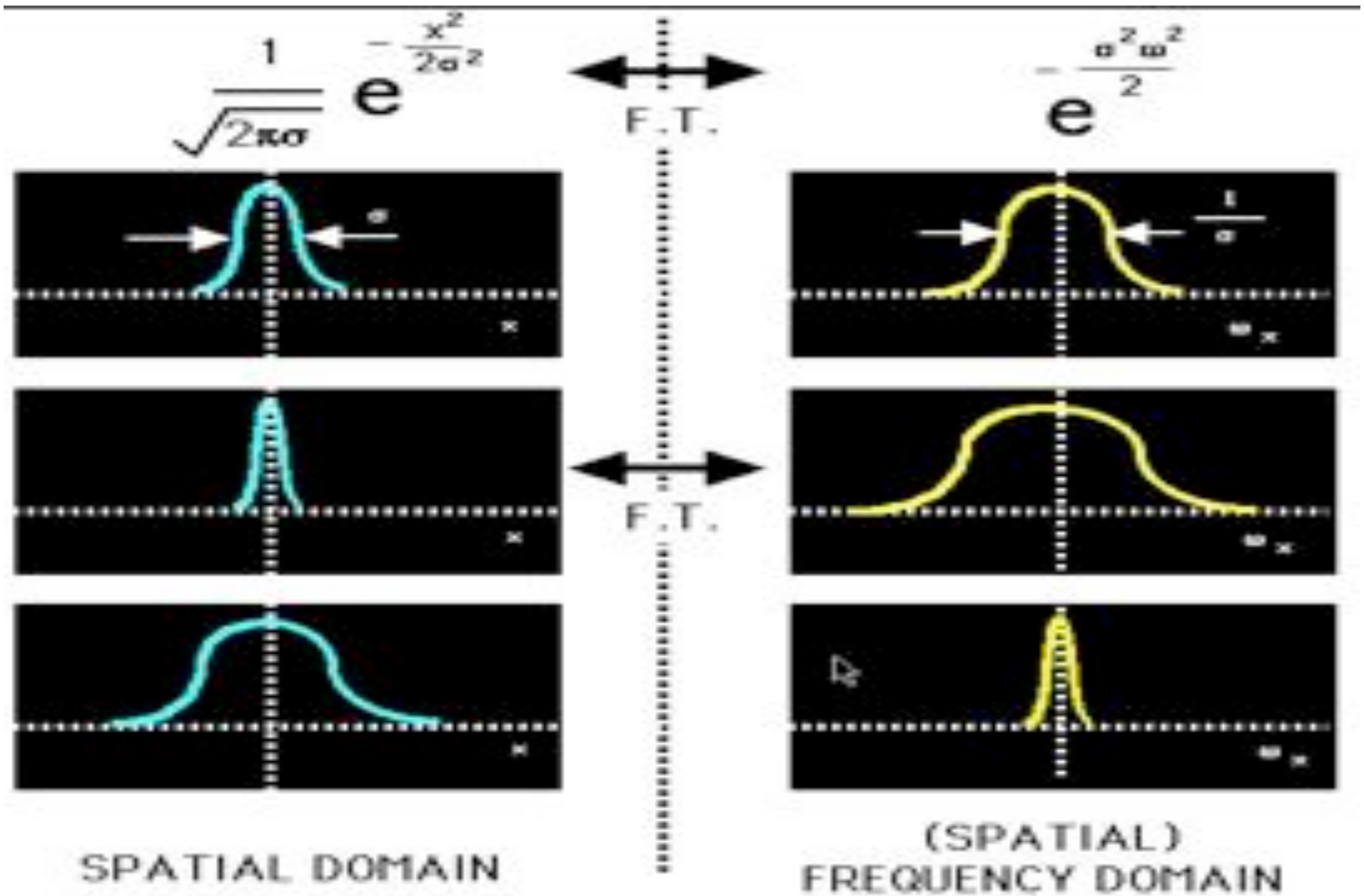
then $\mathscr{F}$ f(x) = F(s) $G^*(s)$ - *Correlation theorem.*

We will make a lot of use of (3) and (4) above. Note that in (4) if the functions f and g are the same, the integral is known as the autocorrelation function.

Some useful FT functions you need to know:



An easy one to remember is that the FT of Gaussian is another Gaussian:



A general thing about FTs to keep in mind, is that a function which is *wide* in one domain is *narrow* in the other, and vice-versa (see above).

In parabolic telescopes (see below) incoming EM-wave electric field oscillations induce voltage oscillations at the *antenna focus*, in a device called a *feed*.

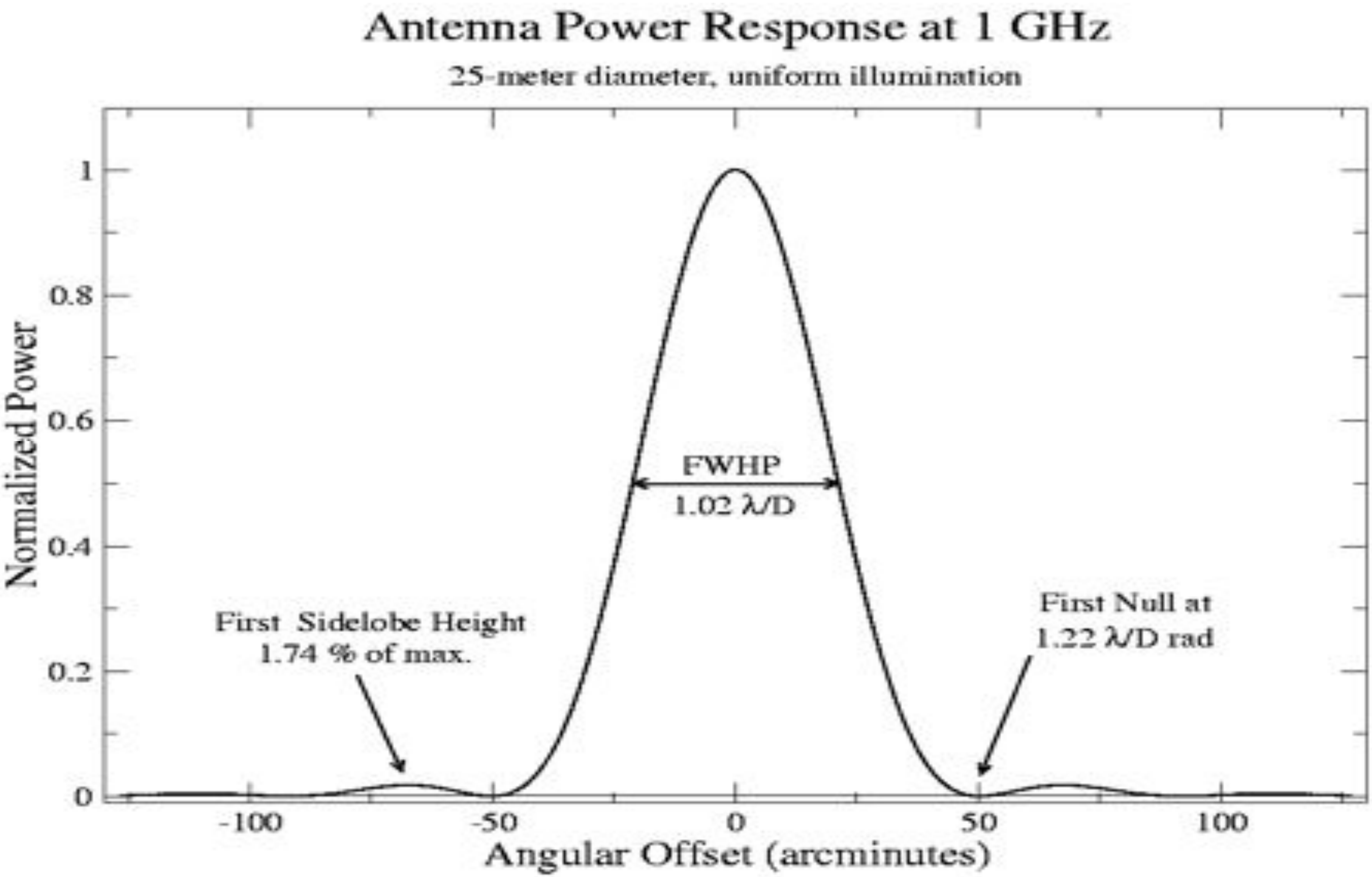
Radio sources are so far away the incoming signals can be assumed to be plane waves.

At cm and mm wavelengths, parabolic collectors are usually optimal for focusing the incoming plane-waves at the focus - where the feed is placed.

alt-az mount

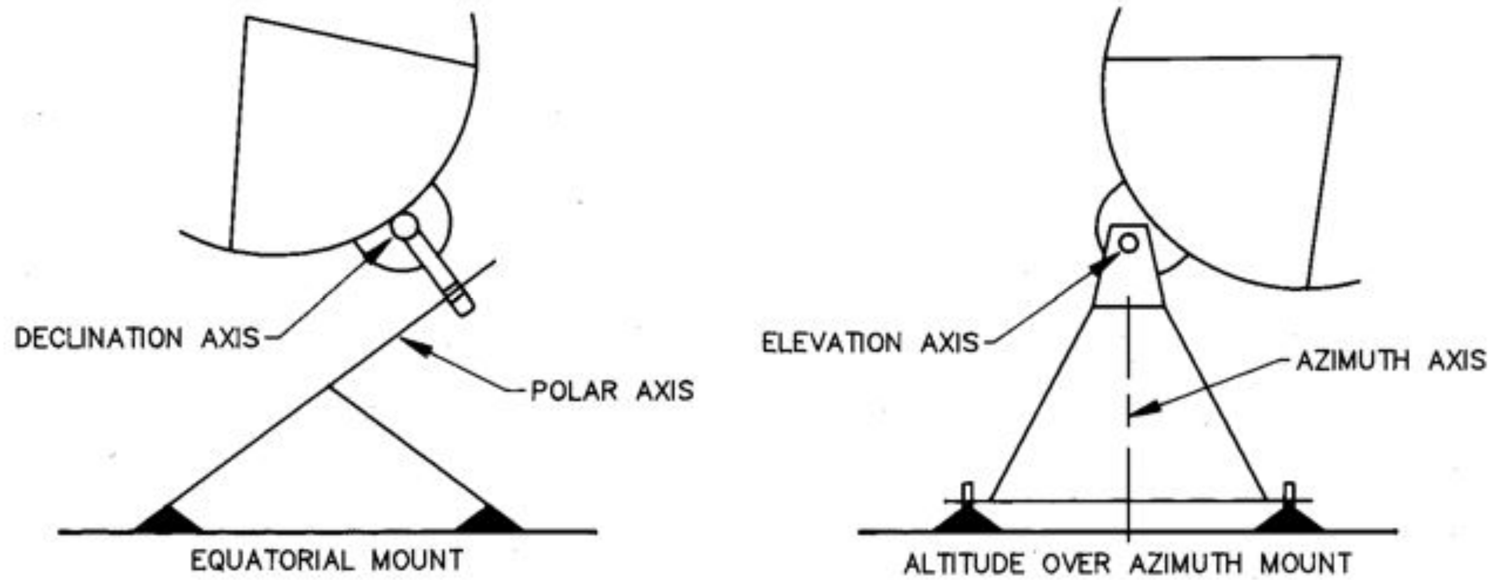
Equitorial (polar) mount

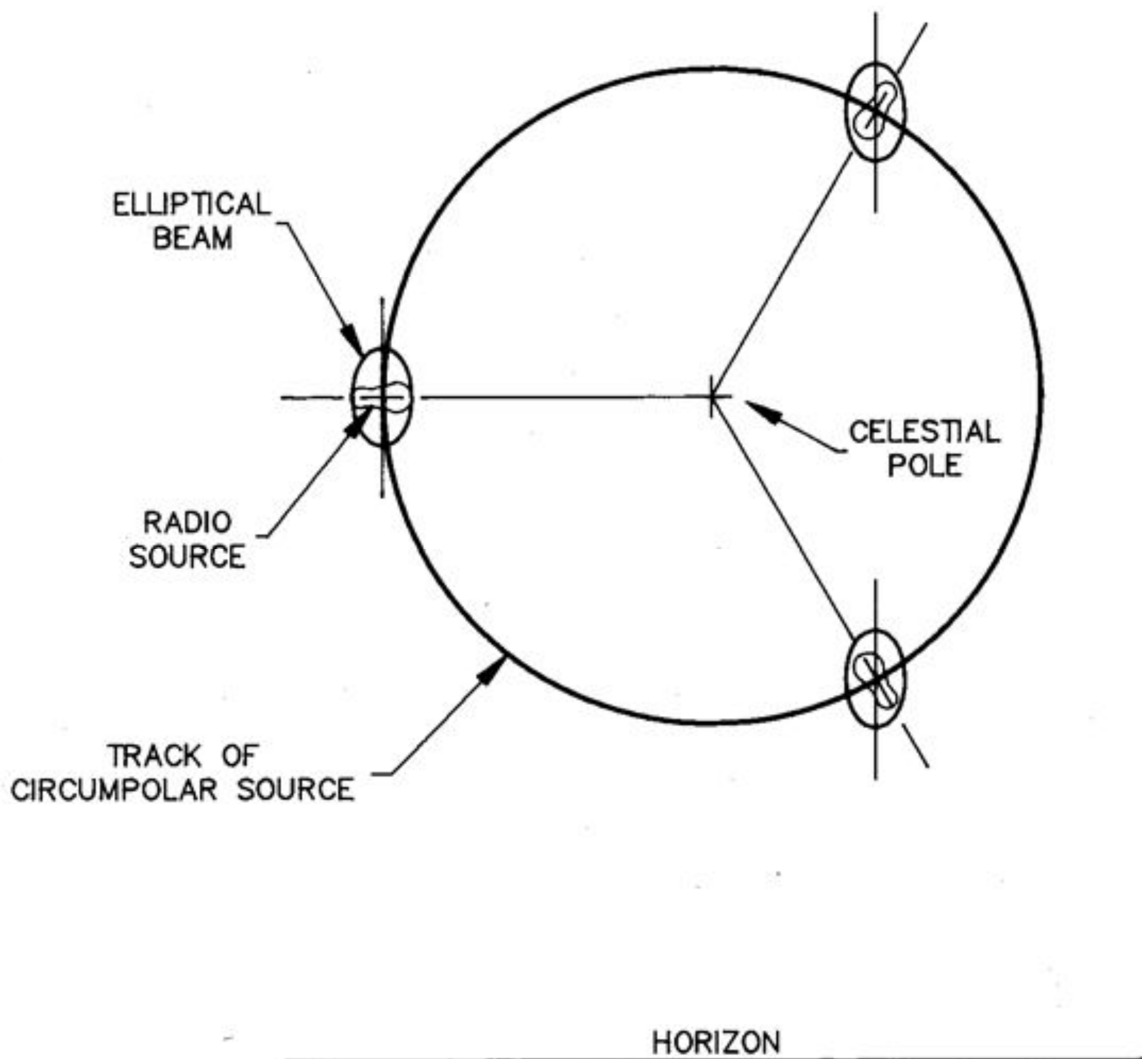
The response of a uniformly illuminated circular parabolic antenna of 25-metre diameter, at a frequency of 1 GHz.



Different types of mount:

Modern antennas are mostly alt-az because they are cheaper to build.



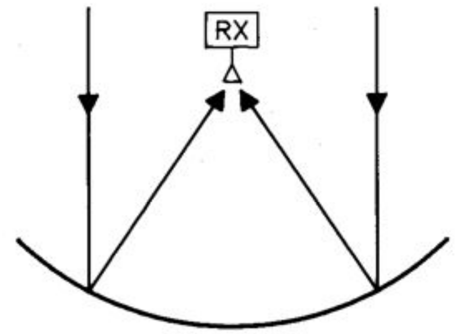


Disadvantage of alt-az telescopes is that the orientation of the telescope beam changes as the source moves across the sky.

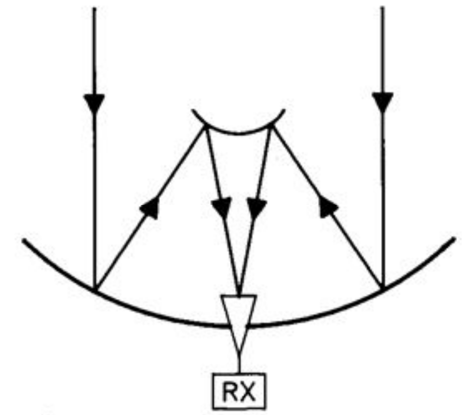
For polarisation measurements, this must first be corrected for (usually in software).

Reflector types

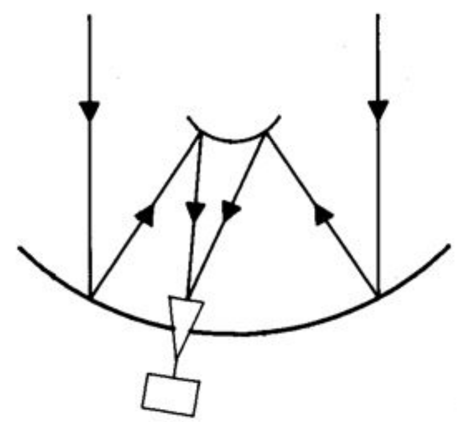
Prime Focus



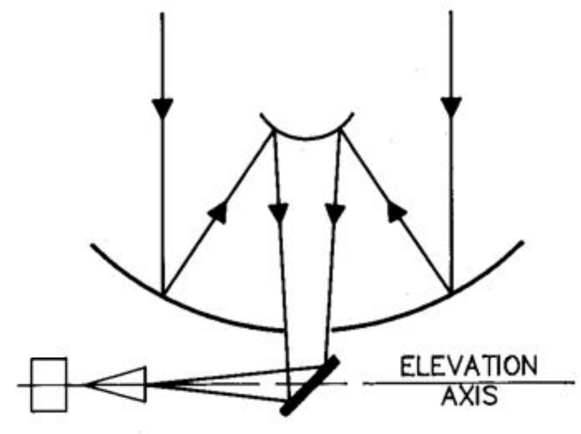
Cassegrain Focus



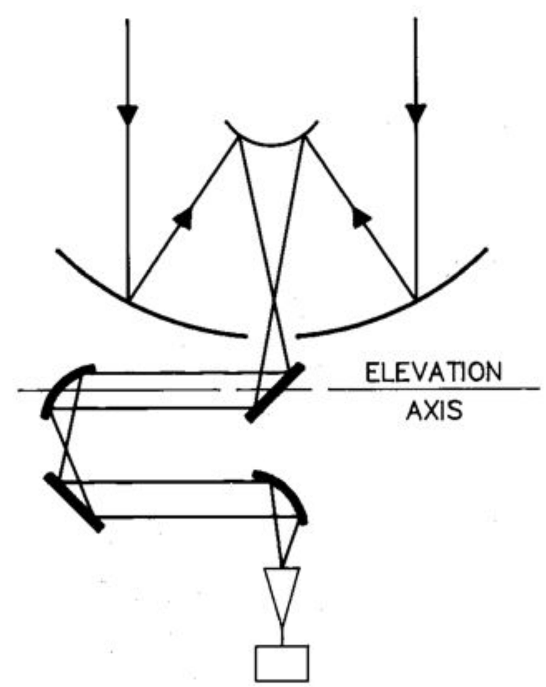
Offset Cassegrain



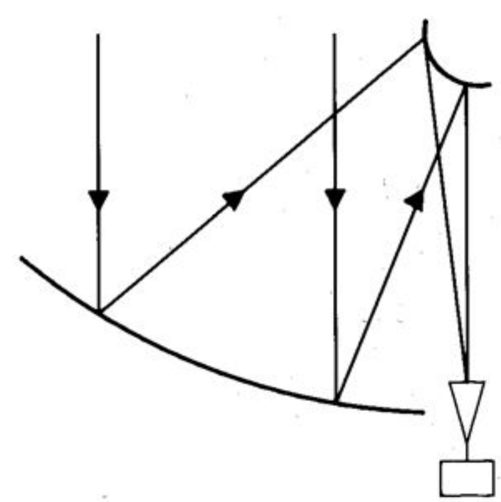
Naysmith



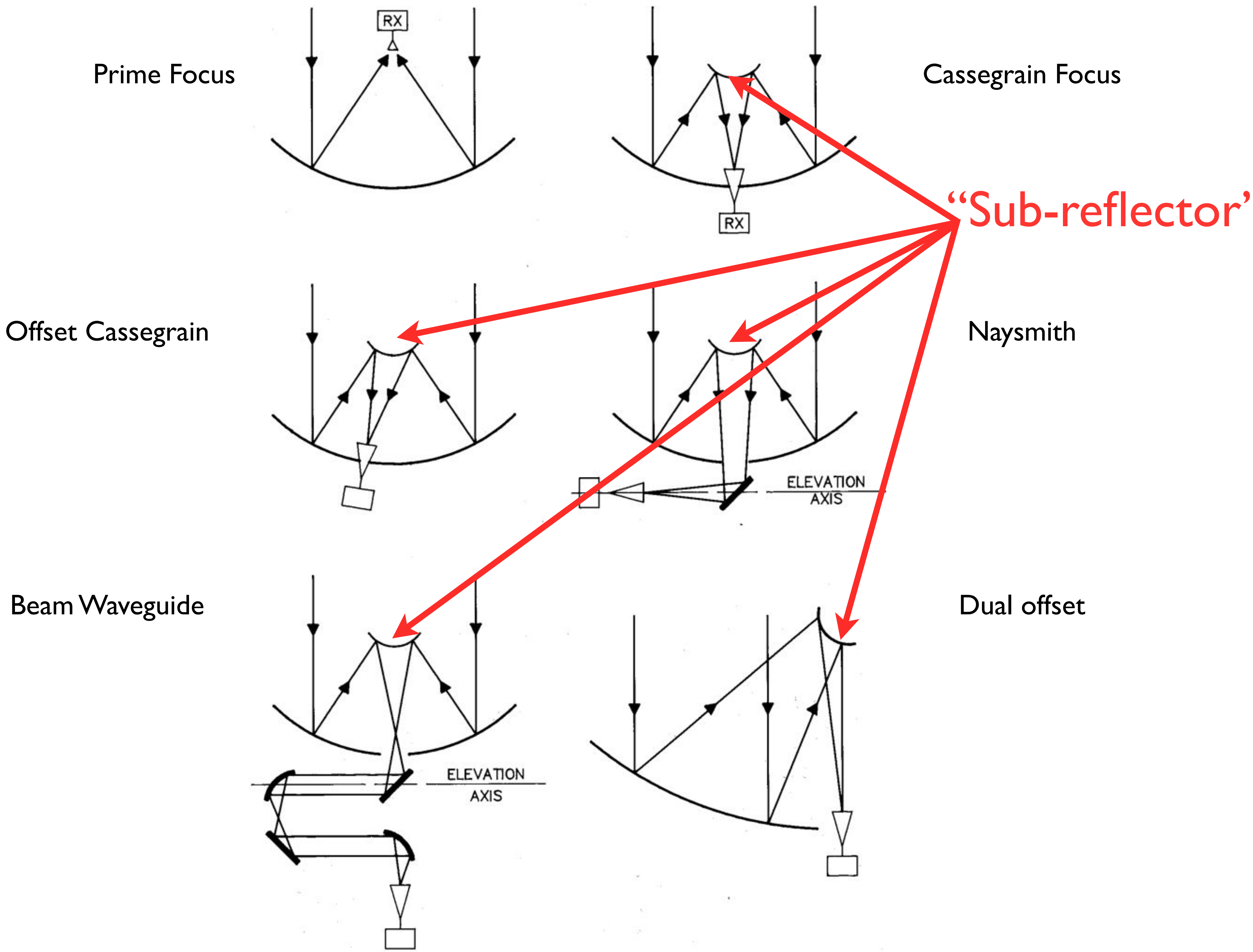
Beam Waveguide



Dual offset



Reflector types



Reflector types

Prime Focus
e.g. GMRT

Cassegrain Focus
e.g. Mopra (AT)

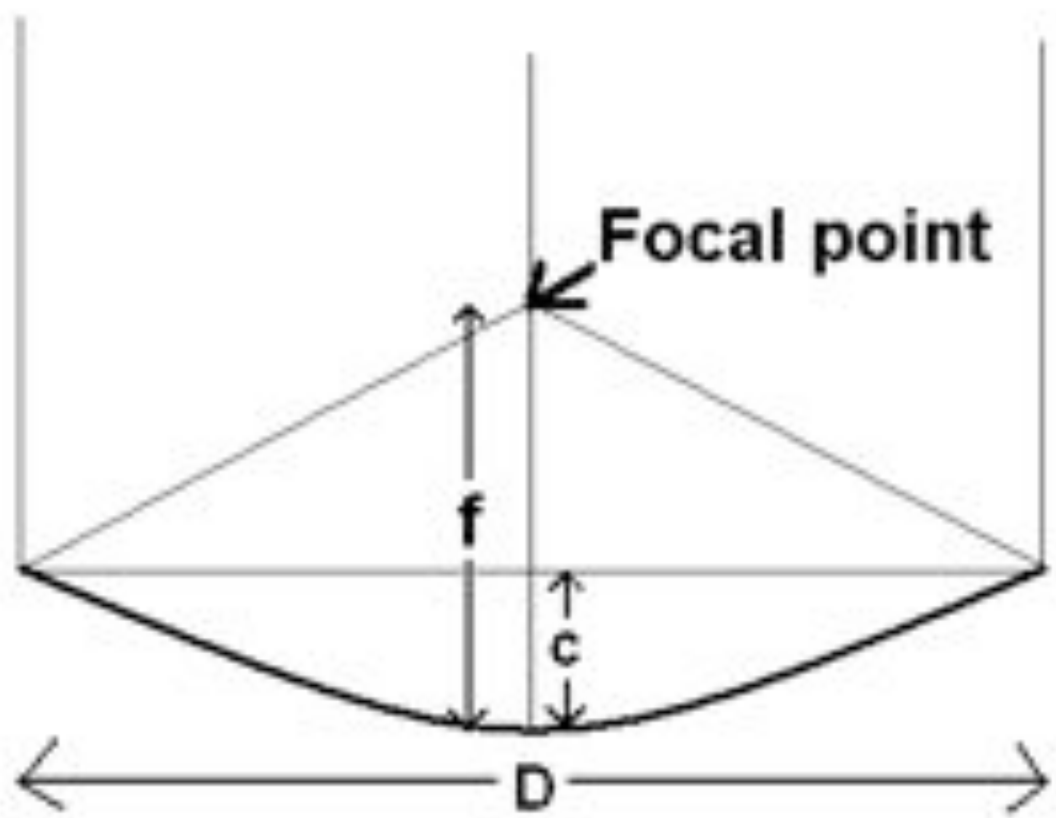
Offset Cassegrain
e.g. VLA and
ALMA

Naysmith
e.g. OVRO

Beam Waveguide
e.g. NRO

Dual gregorian
offset
e.g. ATA

Parabolic Reflector



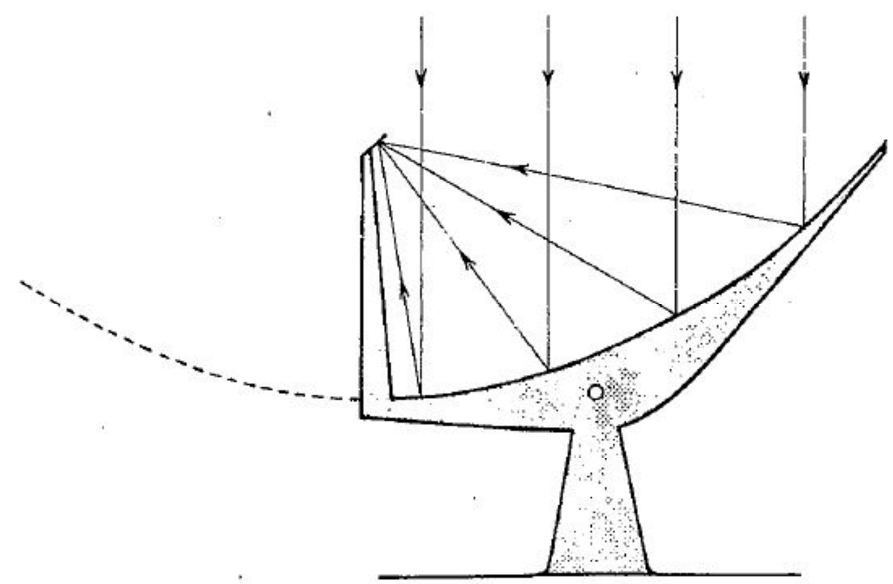
The focal length, f is given by:

$$f = D^2/16c$$

Typically the f/D ("f over D") ratio of a radio telescope is about 0.5. e.g. the WSRT antennas.

This typical value also ensures a rigid structure.

- Prime focus:
  - can be used across full frequency range of antenna but access to receiver is restricted
- Cassegrain (and other non-prime focus e.g. Naysmith and waveguide) provide good access to receivers but low-frequency receivers become impractically large and must be placed at prime focus.
- Off-axis Cassegrain (e.g.VLA antennas) enables frequency flexibility; receivers located in a circle can be quickly rotated to the focus. However, the assymetry of the offset optics introduces nasty polarisation characteristics that can limit imaging results.



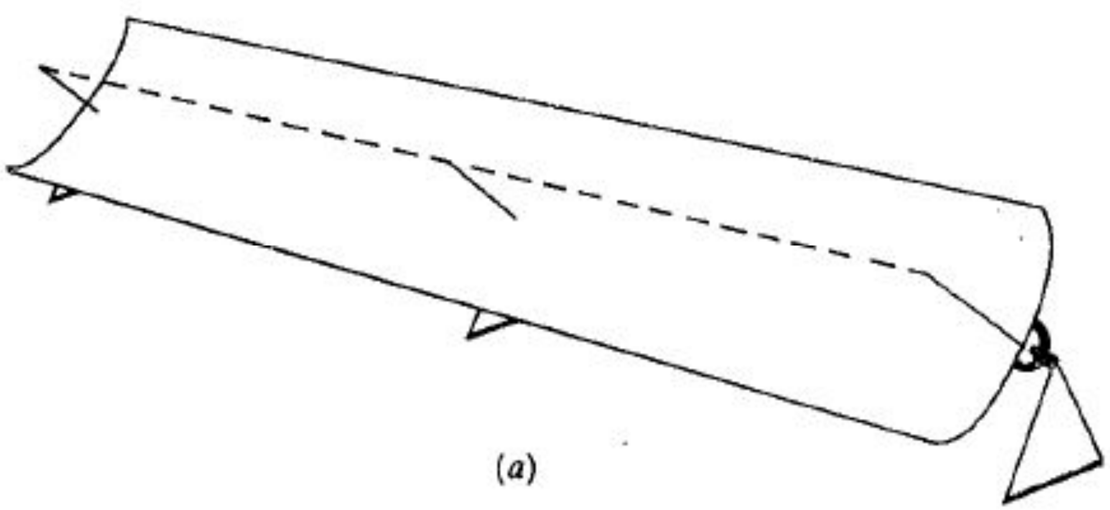
- Offset gregorian (left & above) has no blockage of the aperture.

  A good example of this system includes the largest telescope in the world: the Greenbank Telescope (GBT):

Aside: Some less conventional (weird!)reflector types

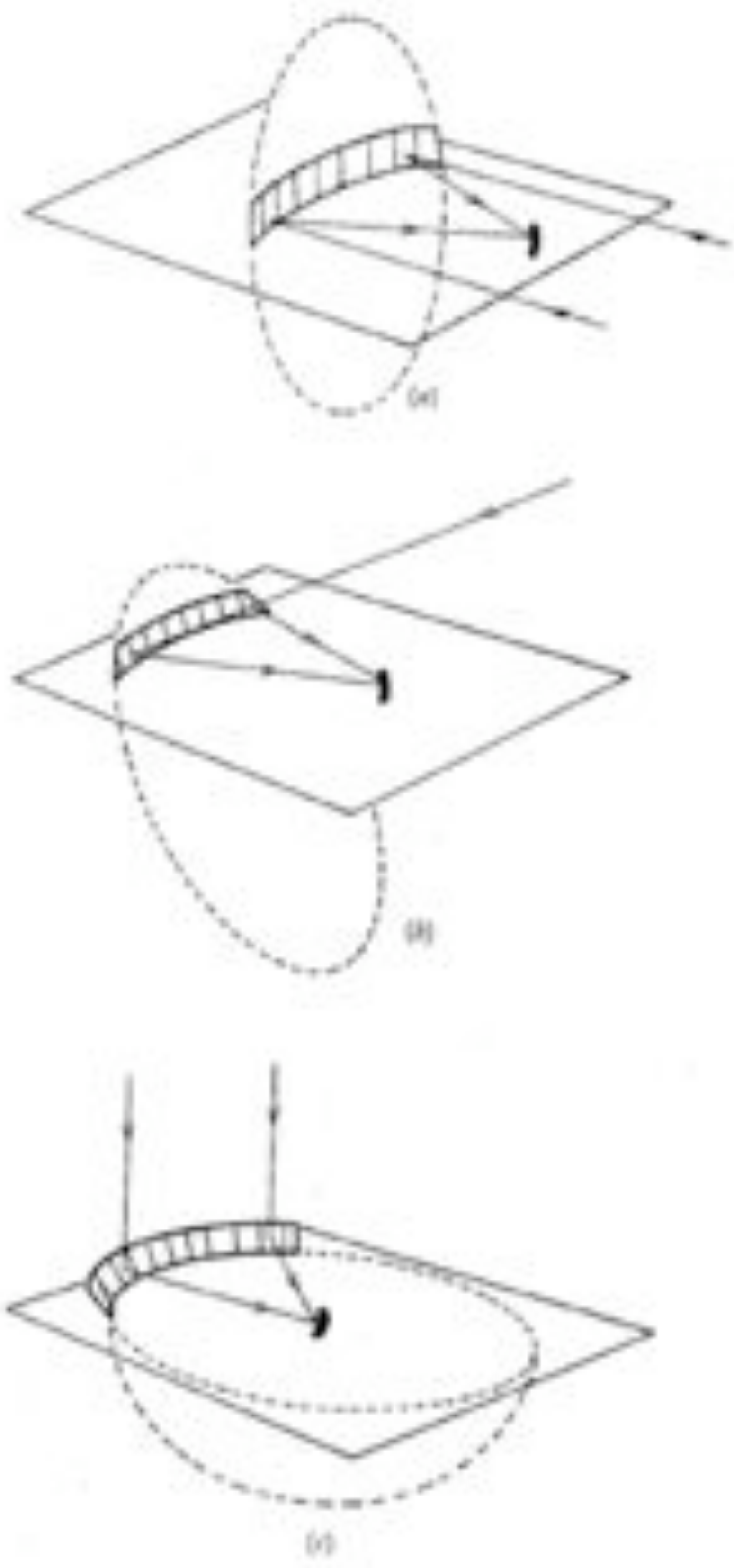
The Jodrell Bank Mark 2 telescope (1964). Was considered to be a prototype of the then planned giant 300-metre MkIV. The aperture is elliptical - the idea was that a 300-metre would require an elliptical surface in order to reduce the height of the structure off the ground.

The off-axis cylinder radio telescope at Ooty. India (1970)

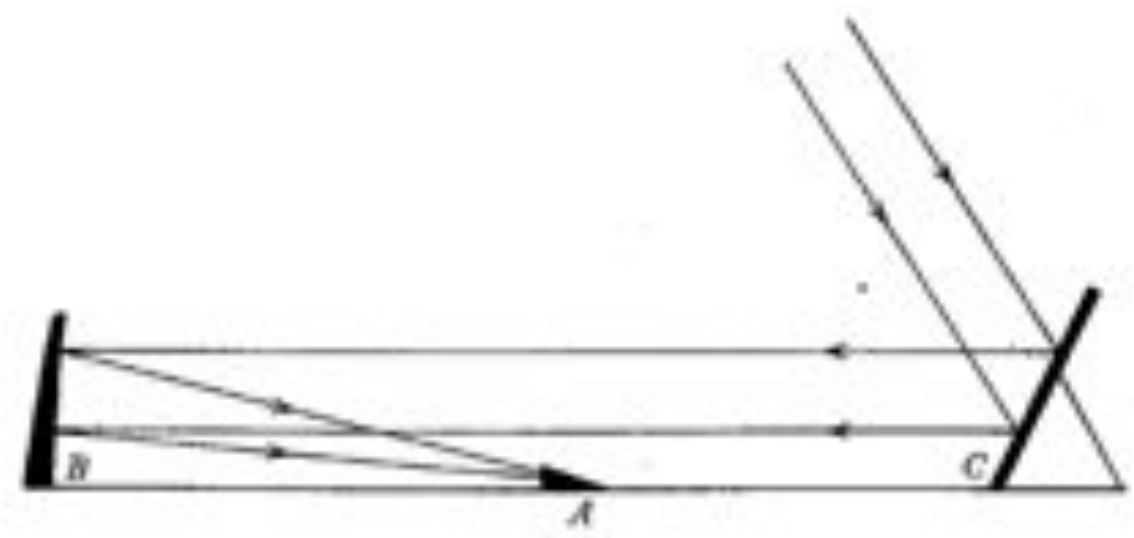


(a)

Instead of building a large paraboloid the Kraus antenna employs (sub-) sections of a parabolic surface. To steer the beam the reflector needs to be tilted:



Fixed paraboloid:



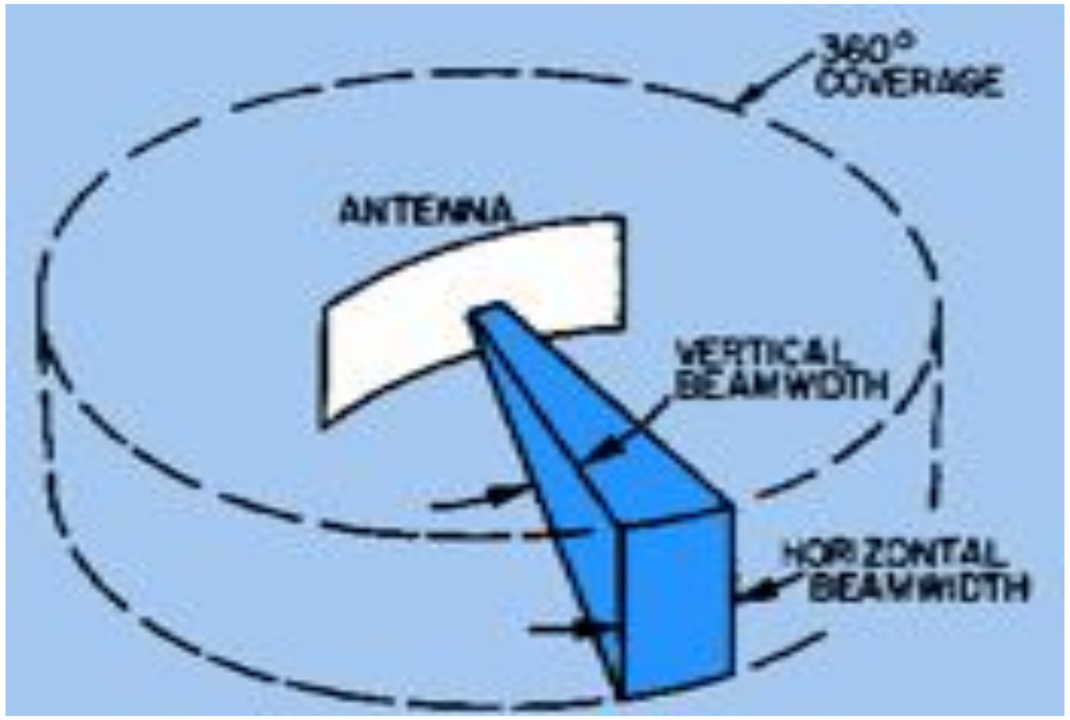
The big-ear antenna built by Kraus (he of the terrible blue book):

Other similar examples: Ratan 600 - Russia

Nancay (France):

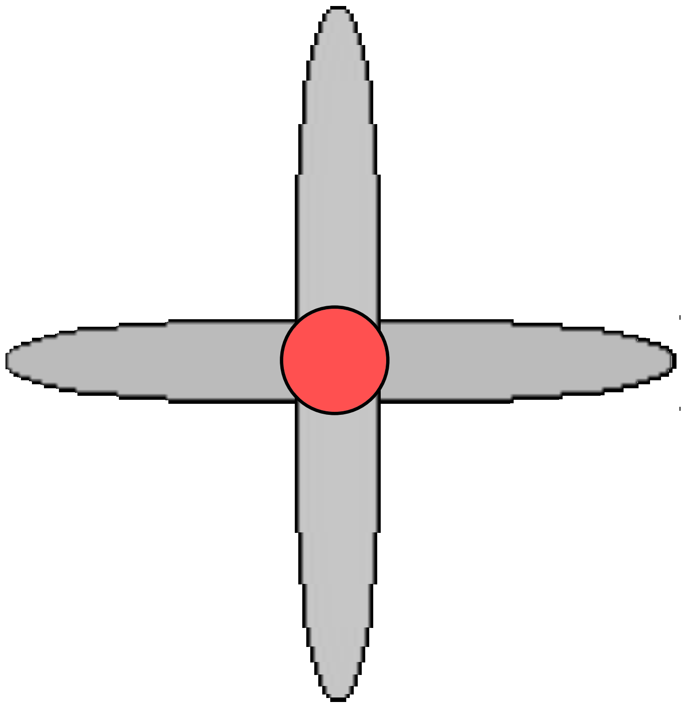
Cross antennas

Instead of building an entire parabola, Cross Antennas employ only a narrow section of a parabola, we get a beam narrow in the antenna's wide direction, and broad in the other direction: .



By observing a source with two orthogonal beams, we can get a 2-d image of the sky.

The cross antenna response is similar to the crossing point of the two beams (but with very high side-lobes):



The first Cross telescope - was built by Bernie Mills in Australia.

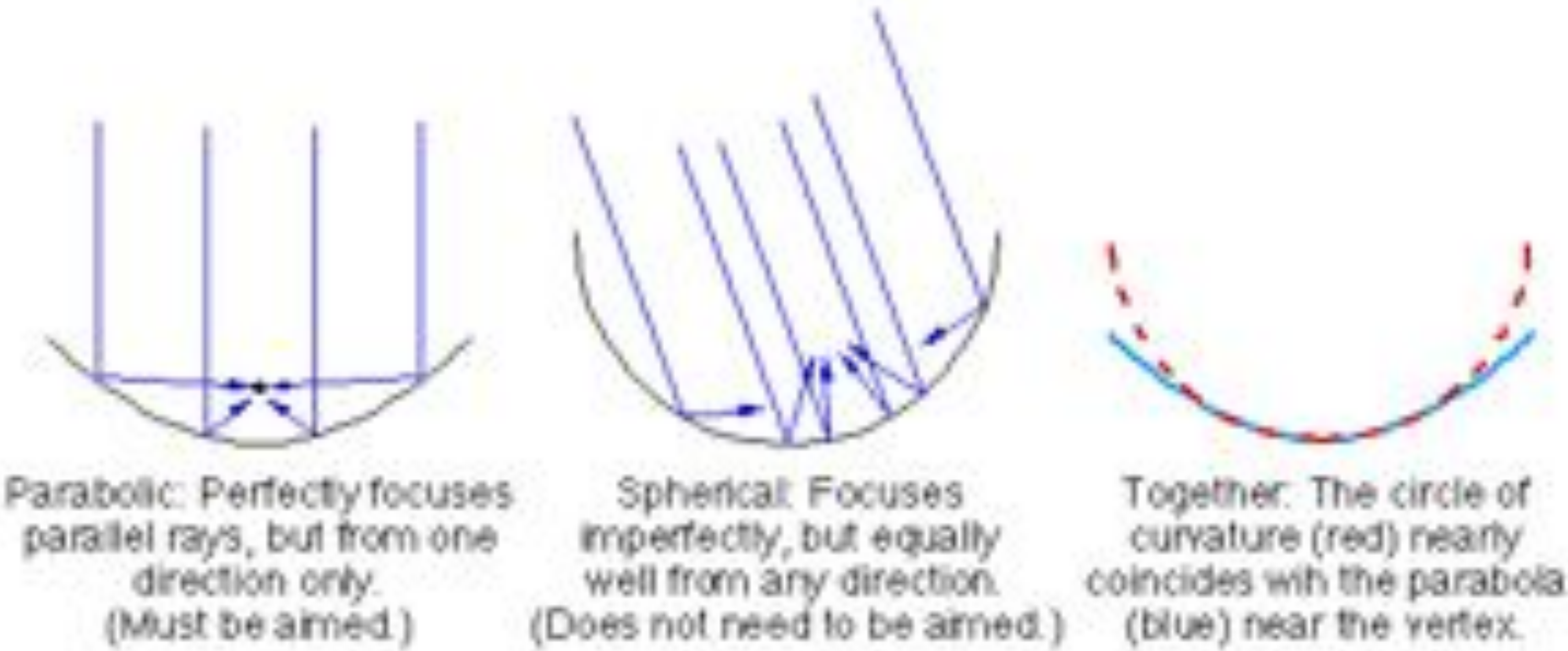
The Mills cross:

MILLS CROSS (CSIRO)

Many other examples:

The 305-m Arecibo telescope is fixed in the ground. A spherical reflector is therefore employed:

While a parabola has a single focus point, a spherical reflector focus the incoming radio waves on a line:



By having a moving secondary a spherical reflector can be pointed in different (but still somewhat limited) directions on the sky.

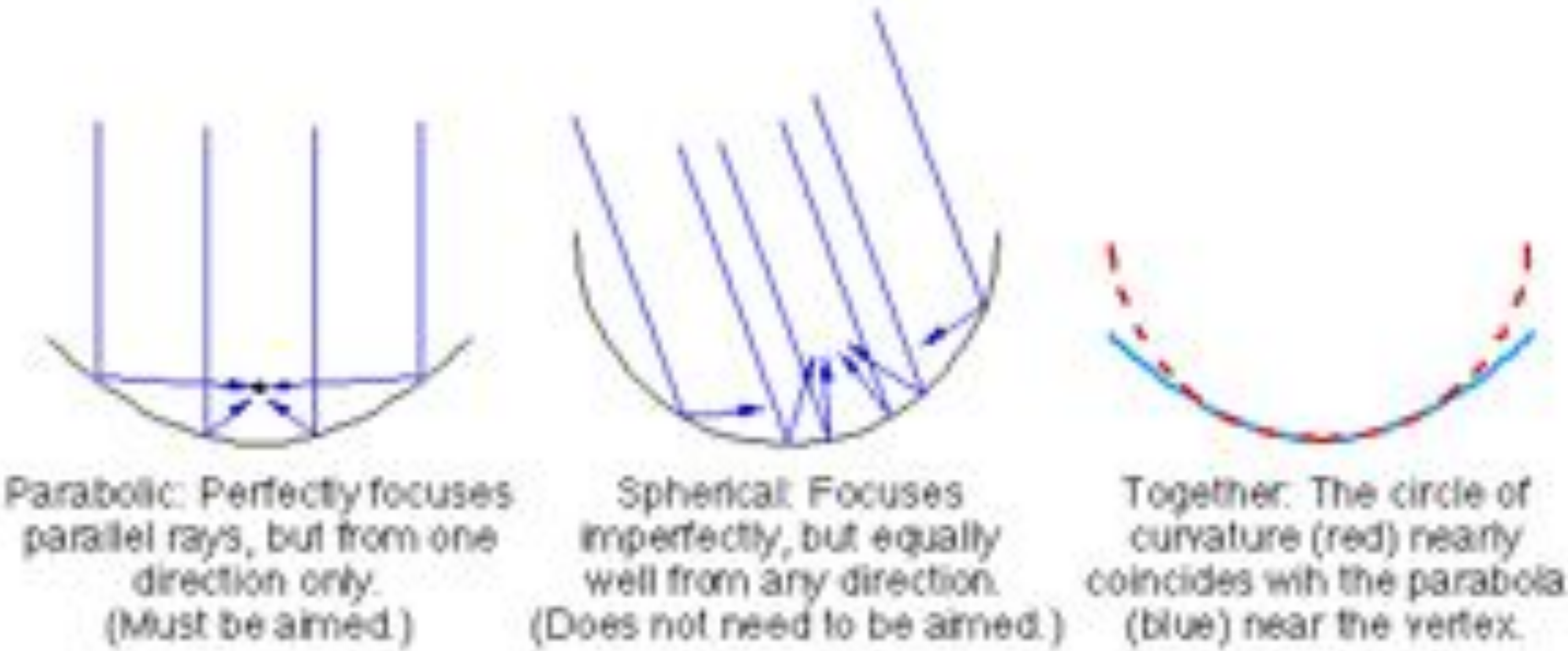
Note that only part of the total surface area is useable for any given direction.

Part of the primary:

Looking on to the surface: quite a lot of litter!

Looking down on the surface from the focus box:

While a parabola has a single focus point, a spherical reflector focus the incoming radio waves on a line:

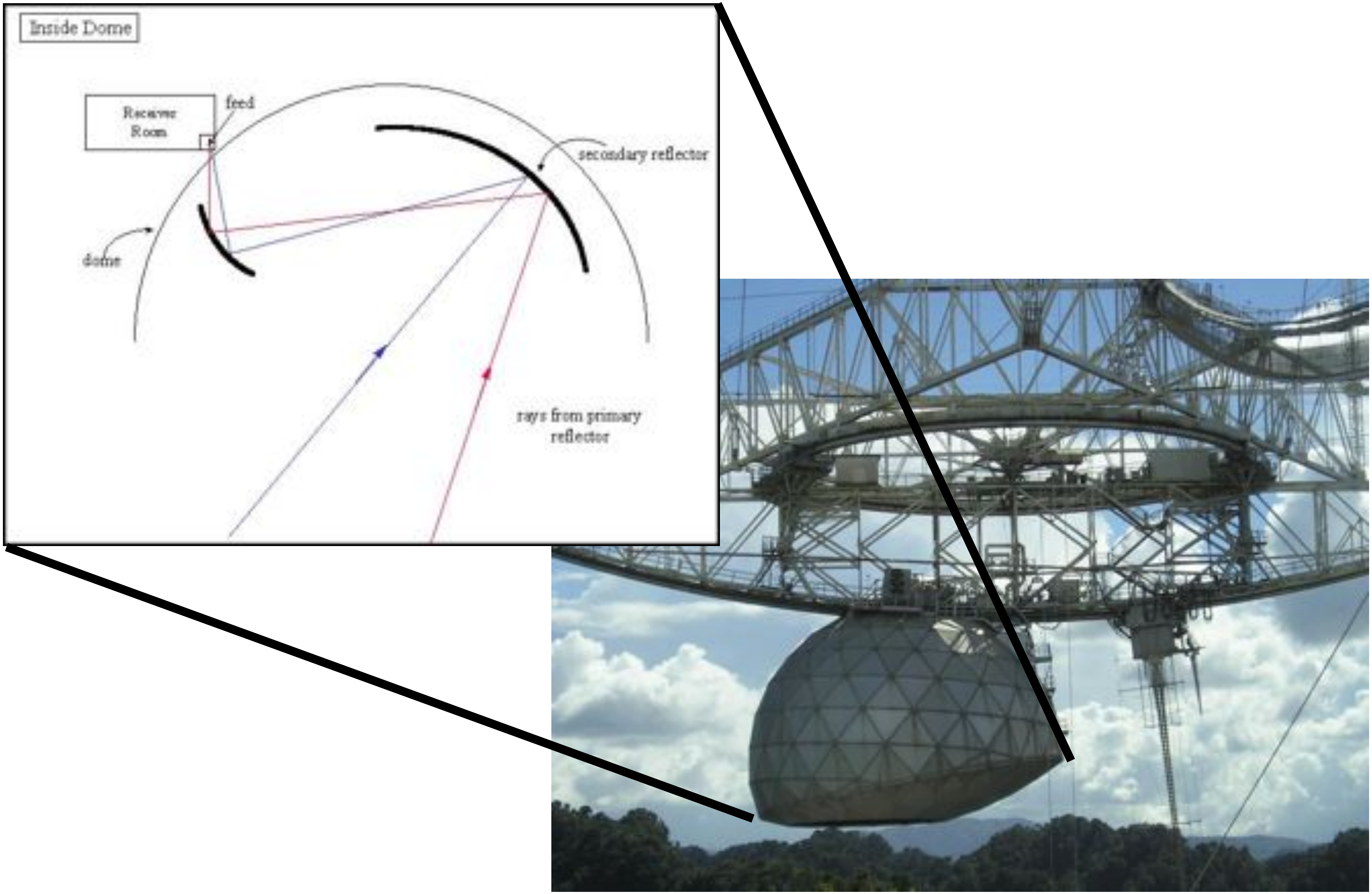


By having a moving secondary a spherical reflector can be pointed in different (but still somewhat limited) directions on the sky.

Note that only part of the total surface area is useable for any given direction.

Arecibo is built in a karst depression. The Gregorian secondary hangs on cables that are supported by 3 large towers:

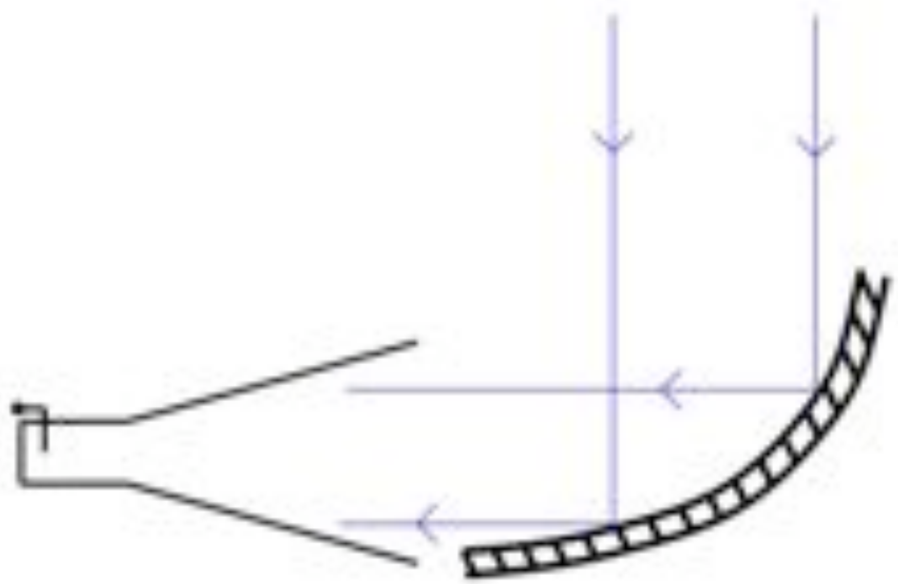
The large secondary feeds a tertiary reflector which in turn feeds a receiver room that has a broad range of receivers.:



Arecibo is an impressive telescope - huge scale:

Even more impresive is what lies under the dish itself: another world... with its own road and river!

Horn antennas:



The reflecting "ear" reflects the incoming radio waves towards a horn or bare dipole.

The Horn Antenna combines several ideal characteristics: it is extremely broad-band, has calculable aperture efficiency, and the sidelobes are so minimal that scarcely any thermal energy is picked up from the ground. Consequently it is an ideal radio telescope for accurate measurements of low levels of weak background radiation.

A very famous example is the horn antenna located at Bell Telephone Laboratories in Holmdel, New Jersey, used by Penzias and Wilson to detect the relic radiation of the big bang.

Horn antennas have many practical applications - they are used in short-range radar systems, e.g. the hand-held radar "guns" used by policemen to measure the speeds of approaching or retreating vehicles.

The Bell Telephone Laboratories horn in Holmdel, New Jersey. Note the rotation axis that permits the horn to be directed at different points in the sky.

Antenna Performance (see Napier SIRA)

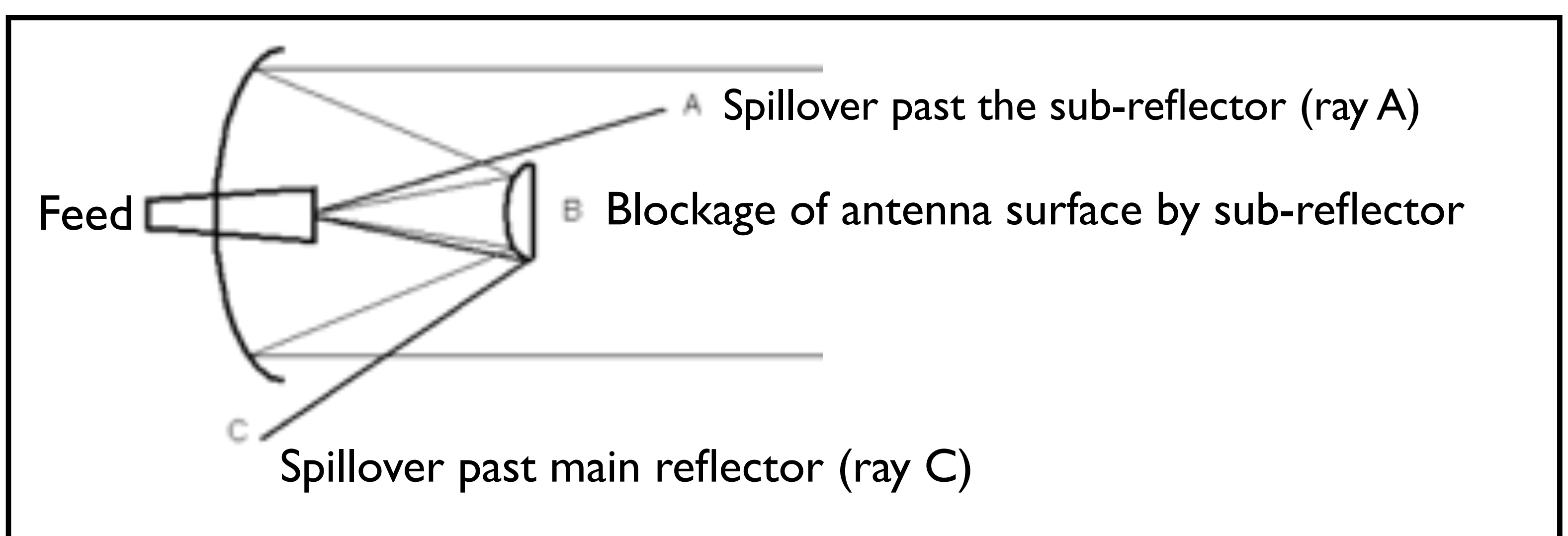
The antenna aperture efficiency η = $\dfrac{\text{Power collected by feed}}{\text{Power incident on antenna}}$

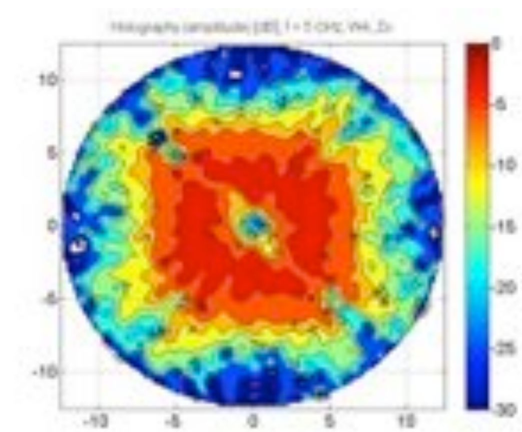
There are many different potential loss factors:

$$\eta = \eta_{sf}\eta_{bl}\eta_{sp}\eta_{t}\eta_{misc} \qquad [6]$$

η ~ 0.4 <==

- Surface efficiency ~ 0.8
- Aperture blockage efficiency ~ 0.8
- Feed spillover efficiency ~ 0.8
- Feed illumination efficiency ~ 0.8
- Misc. - other minor losses e.g feed mis-match.





Feed does not illuminate all of antenna surface equally

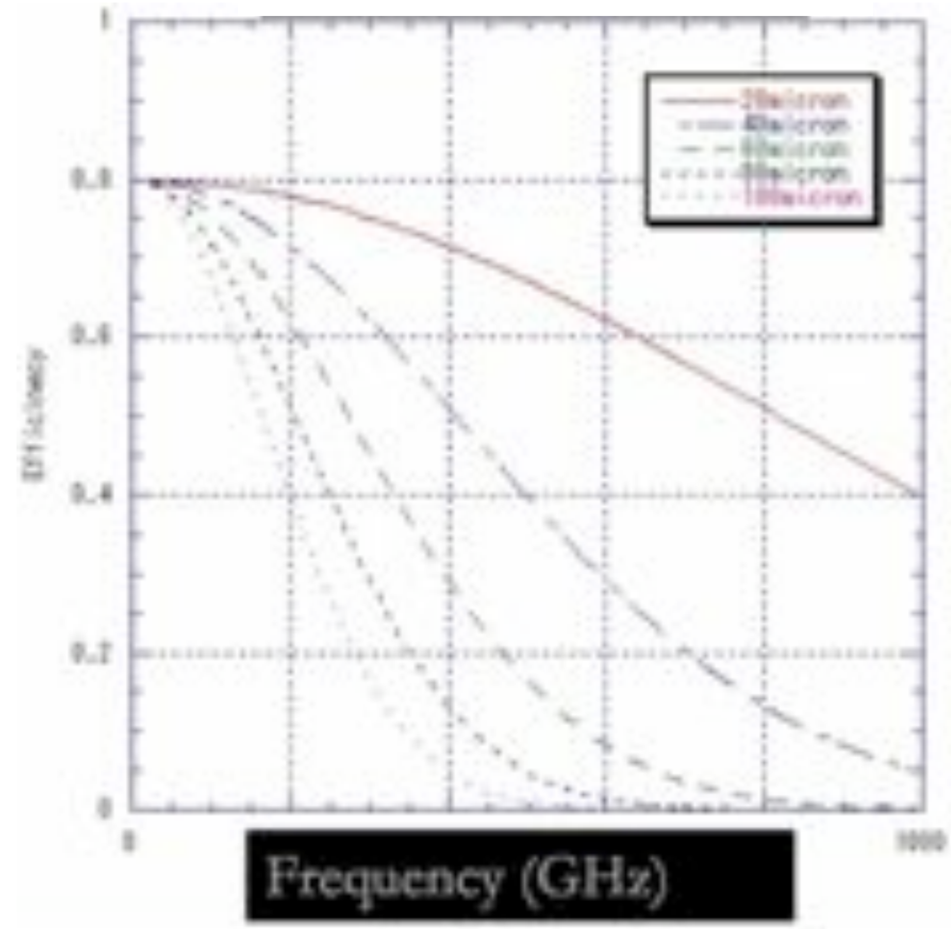
Antenna surface efficiency

According to the Ruze (1966) formula, the surface efficiency of a paraboloid is well described by:

$$\eta_{sf} = e^{-(4\pi\sigma/\lambda)^2} \quad [7]$$

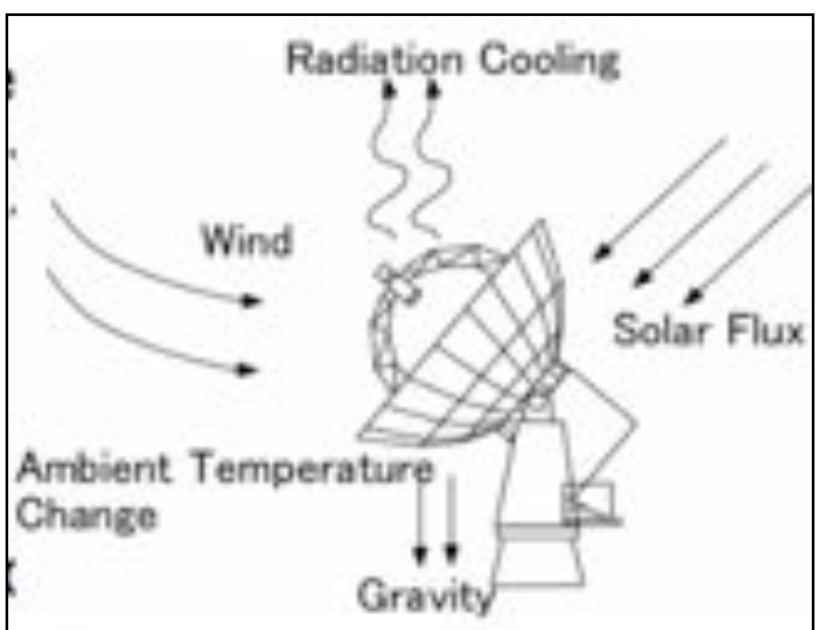
where sigma is the r.m.s. error in the surface of the antenna.

Or re-arranging: $\frac{\sigma}{\lambda} = \frac{1}{4\pi}\sqrt{-ln(\eta_{sf})}$



e.g. For a surface efficiency of 0.7 (typical target value), the required surface error (r.m.s.) is ~ lambda/20.

==> at 7 mm (43 GHz) the surface accuracy must be ~ 350 micron.



==> many different forces acting on an antenna and its surface...

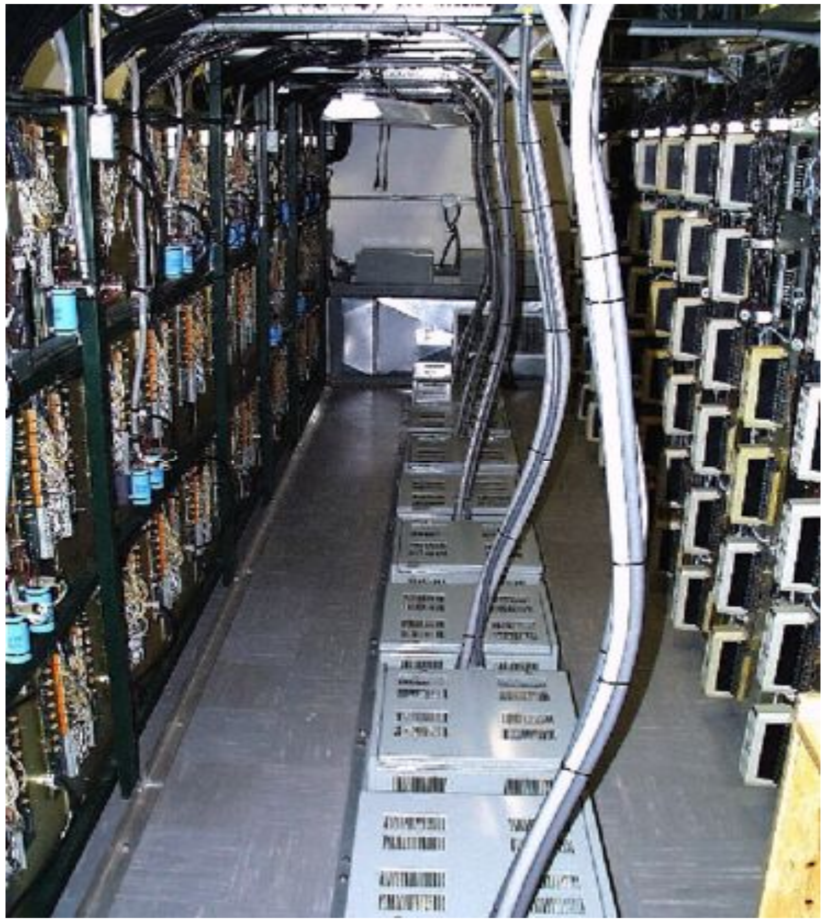
Appreciating the scale of large radio telescopes....

How can we possibly achieve a 350 μm accuracy *(the thickness of three human hairs)* – over a 100 metre diameter surface – an area equal to 2 football fields!

==> *"active surface".*

GBT Surface has 2004 panels
average panel rms: 68μm.

More than 2000 precision actuators are located under the surface panel corners

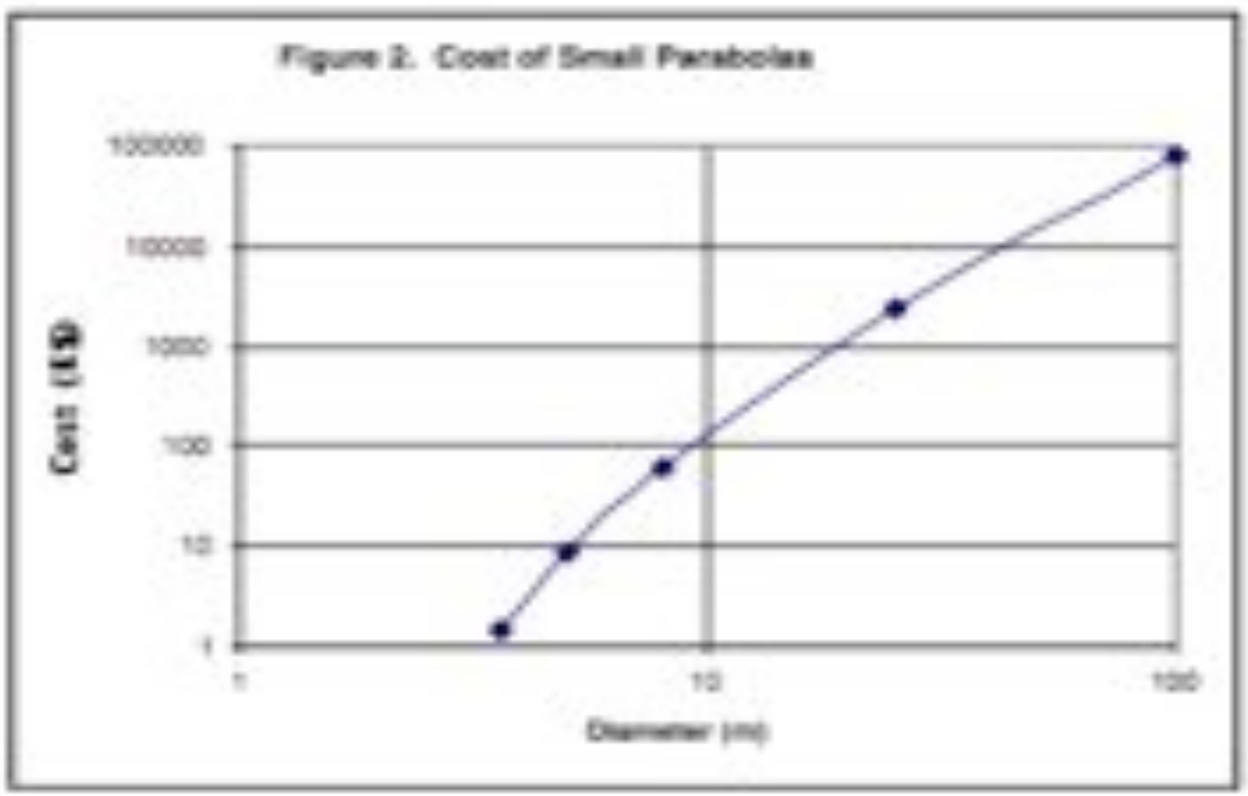


Actuator Control Room (left):
26000 control and supply wires terminate in this room!

How big can parabolic radio telescopes be ?

As the size (diameter) of a radio telescope increases, the gravitational and wind loads on the structure become difficult to manage. The worst problem is the problem of surviving a storm. The degree of wind distortion between paraboloids of different diameters (D) scales as D^3.

The cost of antennas also scales roughly as D^3.



Telescopes like the Jodrell Bank Mark V (right) with a diameter of ~ 305 metres (1970), will probably always remain in model form!

Aside: Power ratios (decibels)

In radio astronomy, decibels are often used to quantify changes in signal level as they pass through the antenna system.

We define power gain (e.g. by an amplifier) as:

$$Gain_{dB} = 10\log(\frac{P_{out}}{P_{in}})$$

We define power loss (e.g. cables) as:

$$Loss_{dB} = 10\log(\frac{P_{in}}{P_{out}})$$

Power gain (in terms of voltages) as:

$$Gain_{dB} = 20\log(\frac{V_{out}}{V_{in}})$$

Absolute Power relative to 1 watt:

$$Power_{dBW} = 10\log(\frac{P}{Watt})$$

Absolute Power relative to 1 milliwatt:

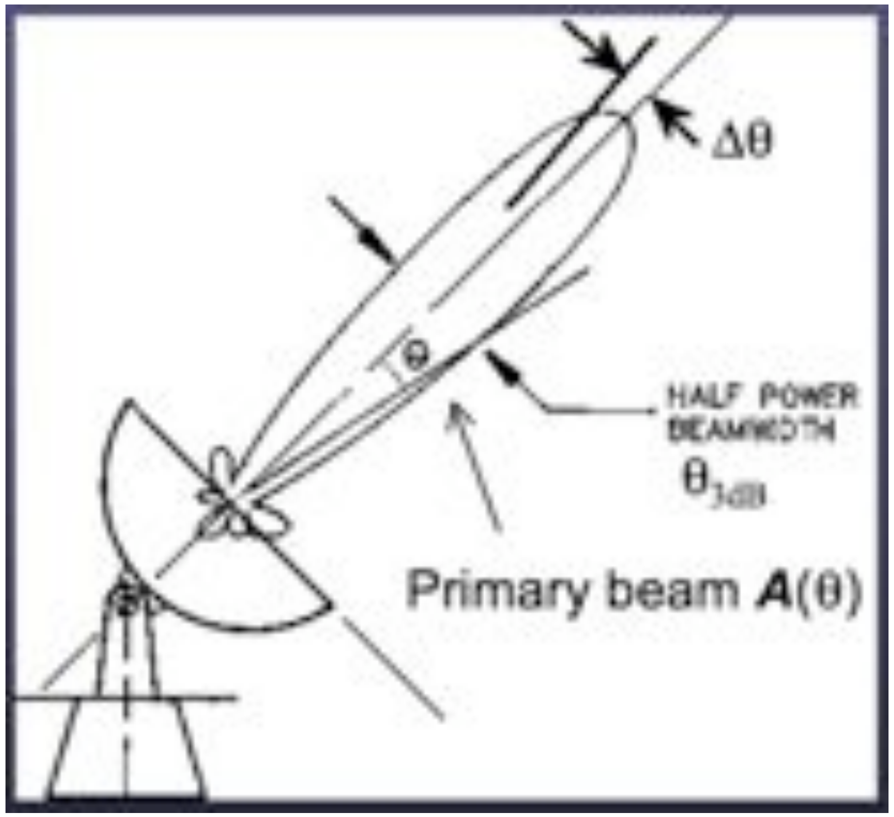
$$Power_{dBm} = 10\log(\frac{P}{mWatt})$$

dB invented by Alexander Graham Bell at Bell Labs.

e.g. a 3dB attenuation of signal power = 50% of signal power being lost.

N.B. a useful feature of dB, is that the total gain or losses associated with a number of inter-connected components is simply the sum of the gains and losses in dB of the individual components [log(abc)=log (a)+log(b)+log(c).

Antenna pointing errors $\Delta\theta$



WSRT pointing errors are typically < 30 arcseconds (or about θ_{3db} /10) at 8 GHz.

The typical goal is: $\Delta\theta < \theta_{3db}/20$

where θ_{3db} is the FWHM of the main lobe of the antenna beam.

N.B. If the antenna moves $\theta_{3db}/20$ off the true pointing centre, this will result in < 1% loss of intensity for a source located on the central axis of the beam.

However, a source located at θ_{3db} will see a 10% loss! This can badly affect the quality of a radio source image towards the edge of the field

At higher frequncies (~ 20 GHz) pointing checks are often made on nearby bright sources to update the pointing model (offsets).

Typically pointing becomes more difficult at higher frequencies and with larger antennas (i.e. smaller primary beams).

Antenna servo performance

The speed at which an antenna can move from one part of the sky to another is also an important performance factor.

This is required for:

(i) observing efficiency

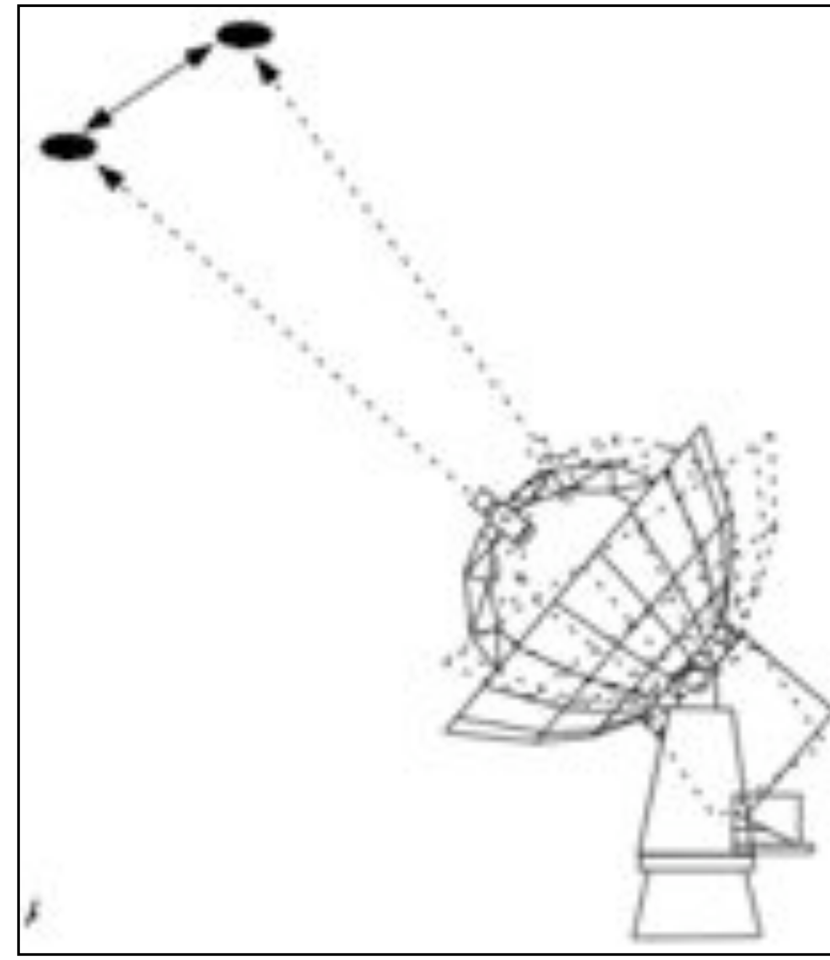
(ii) calibration (e.g. fast switching between nearby sources in the case of phase-referencing).

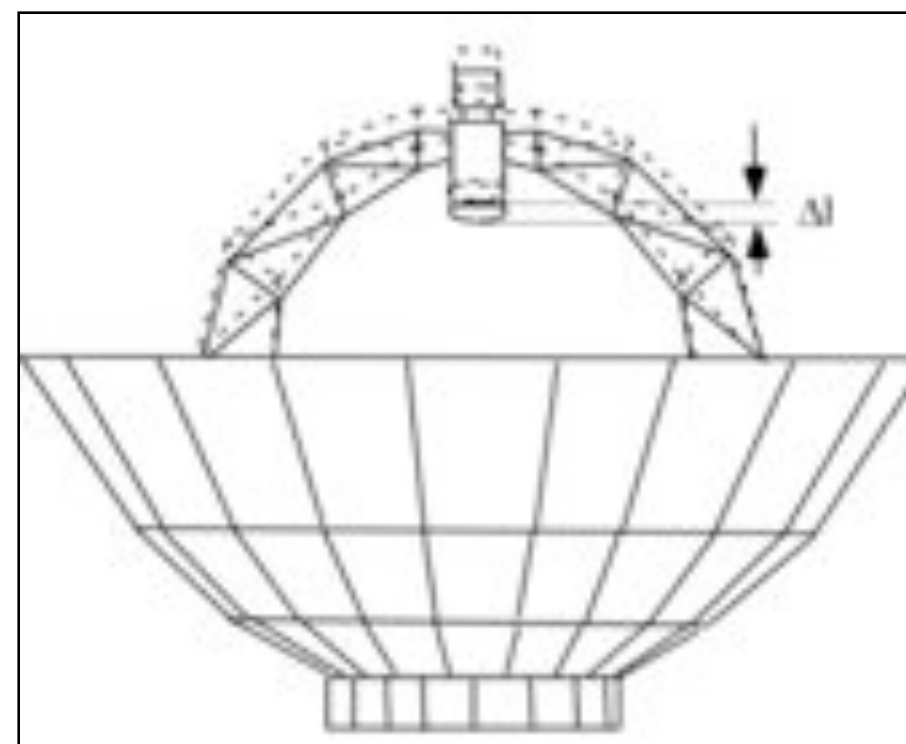
Typical driving rates of modern antennas (e.g. VLBA):

- 90 deg/min in azimuth; 30 deg/min in elevation;
- Settle time ~ 2 secs;
- Time to accelerate to full speed ~ 2 secs.

A rigid structure is important as this:

- minimises "settle time" - the time it takes for antenna to firmly settle on source.
- maintains the optical geometry of the telescope - important for "phase referencing" (see lecture 7 and right).





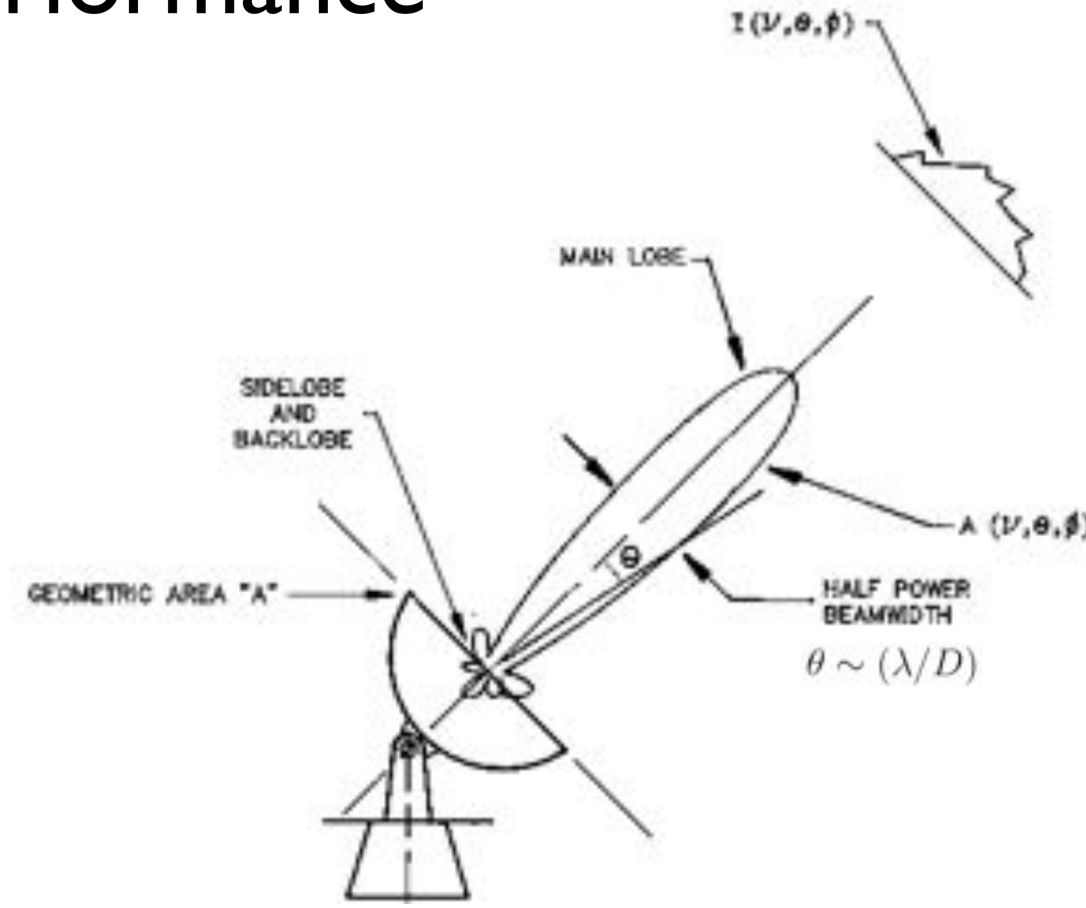
e.g. Lovell telescope (right) old, heavy structure is not stiff - leads to over-shooting, long slew and settling times etc.

e.g. ALMA antennas - v. stiff and highly accurate pointing for THz obs.

Antenna Gain and Performance

The angular response of a parabolic antenna with aperture size, D, observing at a wavelength lambda, is diffraction limited and focused into a cone of solid angle:

$$\Omega_A = \frac{\pi}{4}\theta^2 = \frac{\pi}{4}\frac{\lambda^2}{D^2} \sim \frac{\lambda^2}{D^2} \quad [8]$$



Note if we substitute this into eqn 6a we get:

$$S' = \frac{2kT}{\lambda^2}\left(\frac{\lambda}{D}\right)^2 = 2KT/D^2 \quad [9]$$

$$S = 2\frac{P}{\eta A d\nu}$$

Noting that the power (P) into the receiver is given by eqn [3], by equating with [9] we can write:

$$P = kTdv$$

T is known as the antenna temperature, usually denoted T_{A}. [10]

Eqn[10] is equivalent to the power associated with a resistor placed in a thermal bath at a temperature *T* - the so-called Johnson-Nyquist formula.

The electrons in the resistor undergo random thermal motion, and this random motion causes a current to flow in the resistor. On average there are as many electrons moving in one direction as in the opposite direction, and the average current is zero. The power in the resistor however depends on the square of the current and is not zero. The power is well approximated by the Nyquist formula:

$$P = kTd\nu$$

where k is the same Boltzmann constant as in the Planck law.

In analogy with this, if a power P is available at an antenna's terminals the antenna is defined to have an antenna temperature of

$$T_A = P/(kd\nu)$$

Note that T_A is not the physical temperature of the antenna!

JULY, 1928 PHYSICAL REVIEW VOLUME 32

THERMAL AGITATION OF ELECTRIC CHARGE IN CONDUCTORS*

By H. Nyquist

JULY, 1928 PHYSICAL REVIEW VOLUME 32

THERMAL AGITATION OF ELECTRICITY IN CONDUCTORS

By J. B. Johnson

An isotropic antenna is a (mythical) antenna that collects (or radiates) energy uniformly in all directions. The gain of an antenna is defined as G,

$$G = \frac{\text{Power radiated in a specific direction}}{\text{Power radiated in that direction by an isotropic radiator}}$$

Note that the average gain of any antenna is always 1 if calculated over all angles. The gain of an antenna can also therefore be written as:

$$G = \frac{\text{Solid angle subtended by a sphere}}{\text{Solid angle of antenna beam}} \quad \text{or} \quad G = \frac{4\pi}{\Omega_A} = \frac{4\pi D^2}{\lambda^2} \sim \frac{4\pi A_e}{\lambda^2} \quad [11]$$

N.B. A_e is the effective area , and is always smaller than the geometric area (see eqn 6).
$A_e = \eta A$ where η is typically in the range of 0.4 - 0.8.

Note that from [11] we can also write:

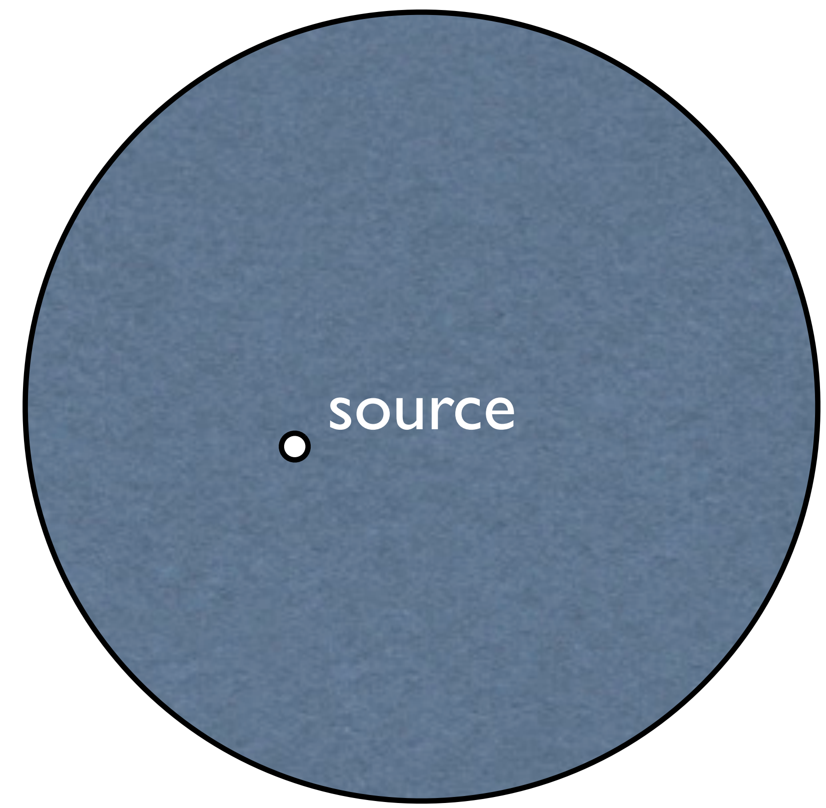
$$A_e \sim \lambda^2/\Omega_A \quad [12]$$

e.g. A 25-metre telescope, observing a 100 milliJansky (mJy) radio source measures an antenna temperature, T_A, of 0.023 Kelvin!

N.B. for a source that is unresolved the antenna temperature, T_a << than T_b (the source brightness temperature). In fact:

$$T_a \sim T_b \textit{ x beam filling factor}$$

The beam filling factor is the fraction of the telescope beam occupied by the source (see right). The radio cores of AGN are usually << the antenna beam - filling factors in excess of ~ 1E-12 are then typical.

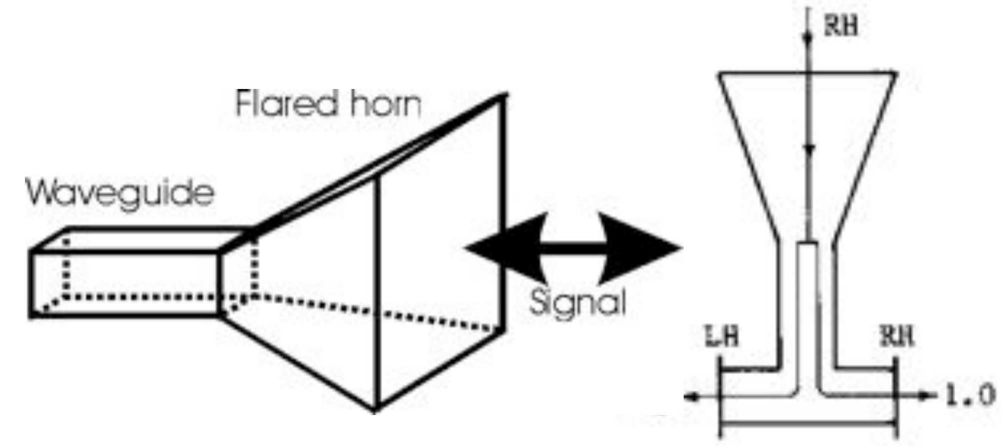


<---Telecope beam, FWHM--->

To measure the brightness temperature of very small sources, like AGN, Very Long Baseline Interferometry must be used.

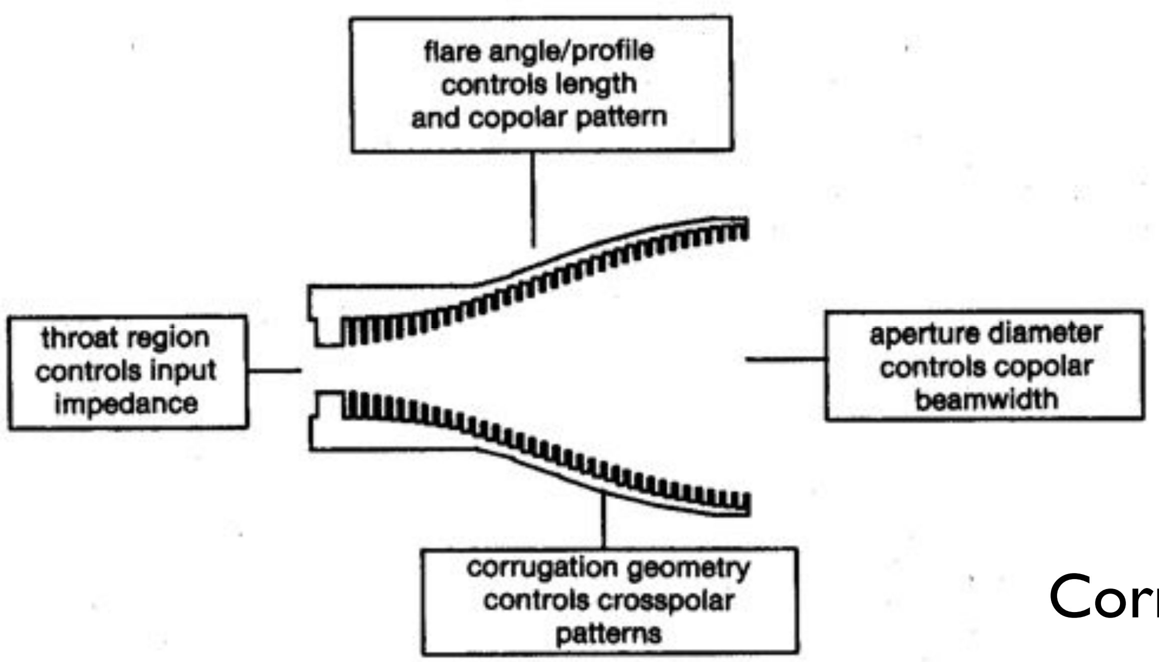
Note also from equation [9] that for an unresolved source, the measured signal will increase as the diameter of the telescope increases.

A *feedhorn* is the front-end of a waveguide that gathers the e-m signals at or near the focal point, and 'conducts' or guides them to a polarisor that splits the signals into oppossite (circular) polarisations (e.g. into independent RH and LH channels - see right).



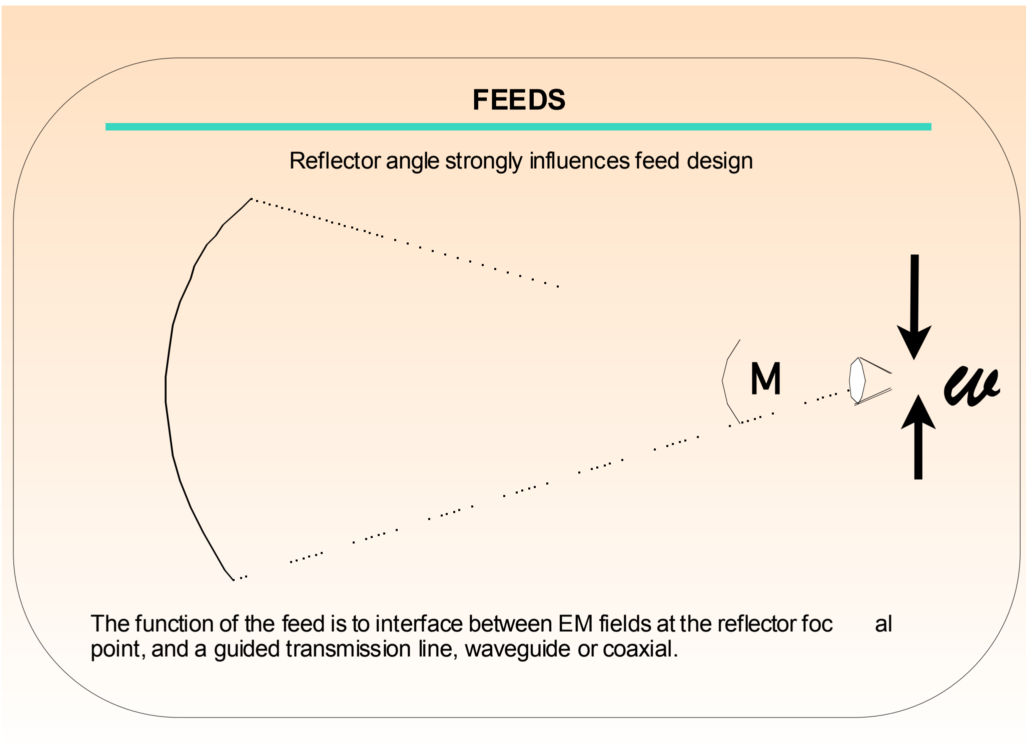
The feedhorn's interior is corrugated in order to increase the surface impedance, so that the wave does not set up voltages in the surface material, but is channelled into a dipole at the end of the horn.

The feedhorn (or "feed") is designed to evenly illuminate the antenna surface. The angle subtended by the reflector as seen by the feed strongly influences the types of feeds which may be used, and the details of their design.



Corrugated horns (above) are the most common.

Generally, the more narrow the angle (M), the larger the feed in units of wavelengths.



Since M ~ D/f (where f is the focal length of the paraboloid), the feed aperture diameter (w) is given by:

$$w \sim \frac{\lambda}{D} f \quad [13]$$

If the f/D ratio is low, say 0.25 to 0.35 then the feed will be close to the dish and needs to spread its power over a wide angle to efficiently illuminate the dish. The feed diameter therefore needs to be small. Note that if the f/D is 0.25 (see earlier slide on parabolic reflectors) the feed is level with the dish aperture, and requires a coverage of 180 degree which is difficult!

If the f/D is large like 0.75 then the feed will be further away from the dish and needs to spread its power into a narrower angle. The feed needs to be of a larger diameter however.

The illumination of the antenna surface by the feed is usually not unifrom.

Feeds are usually designed to under illuminate edges of the dish - in order to avoid spillover from the ground.

Such a design produces a larger beam but smaller side-lobes. Cases (b), (c), (d), (e) - right.

Over illumination of the edges results in a narrower beam (better resolution) but high sidelobes. Cases (f) and (g) - right.

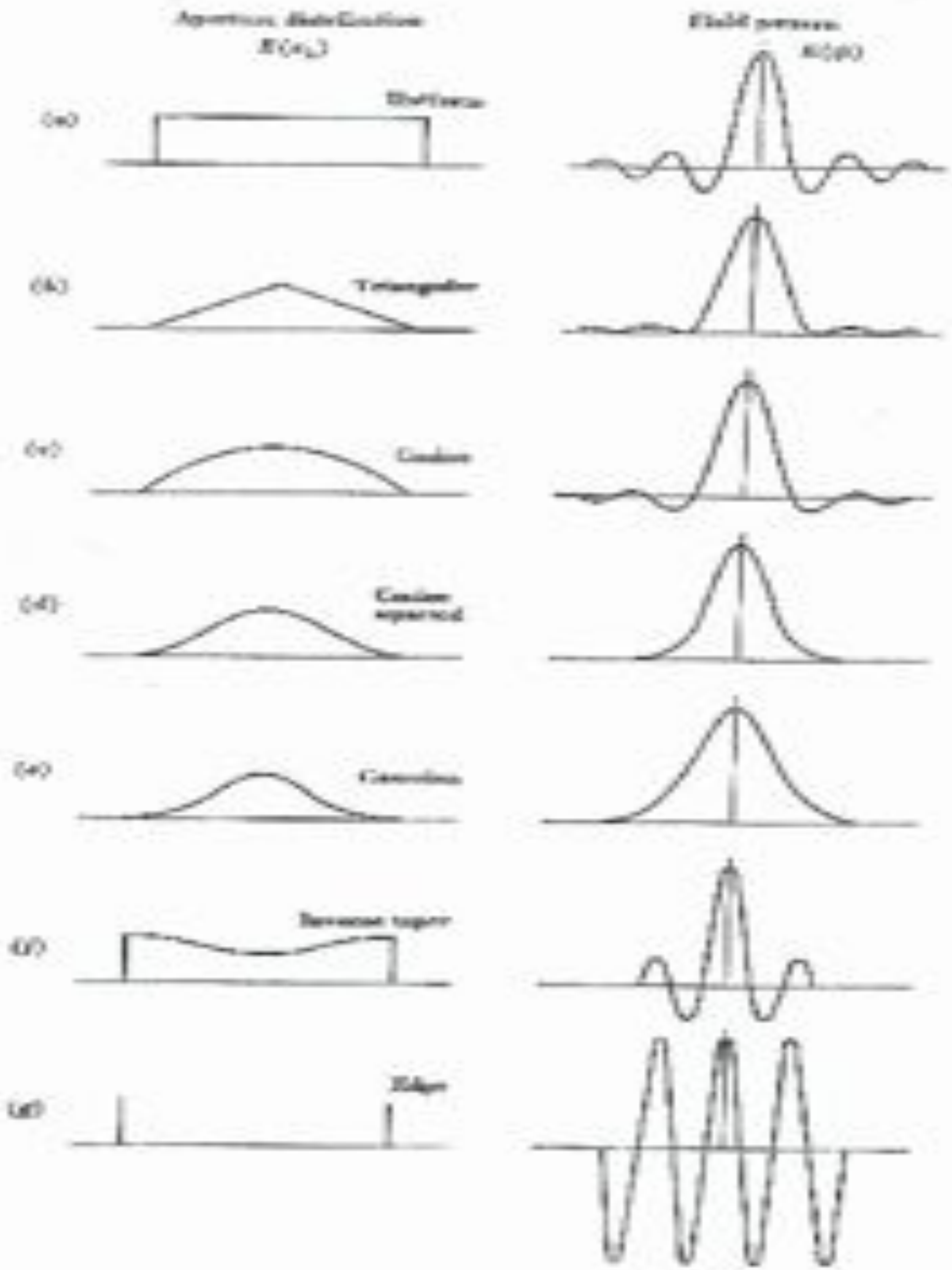
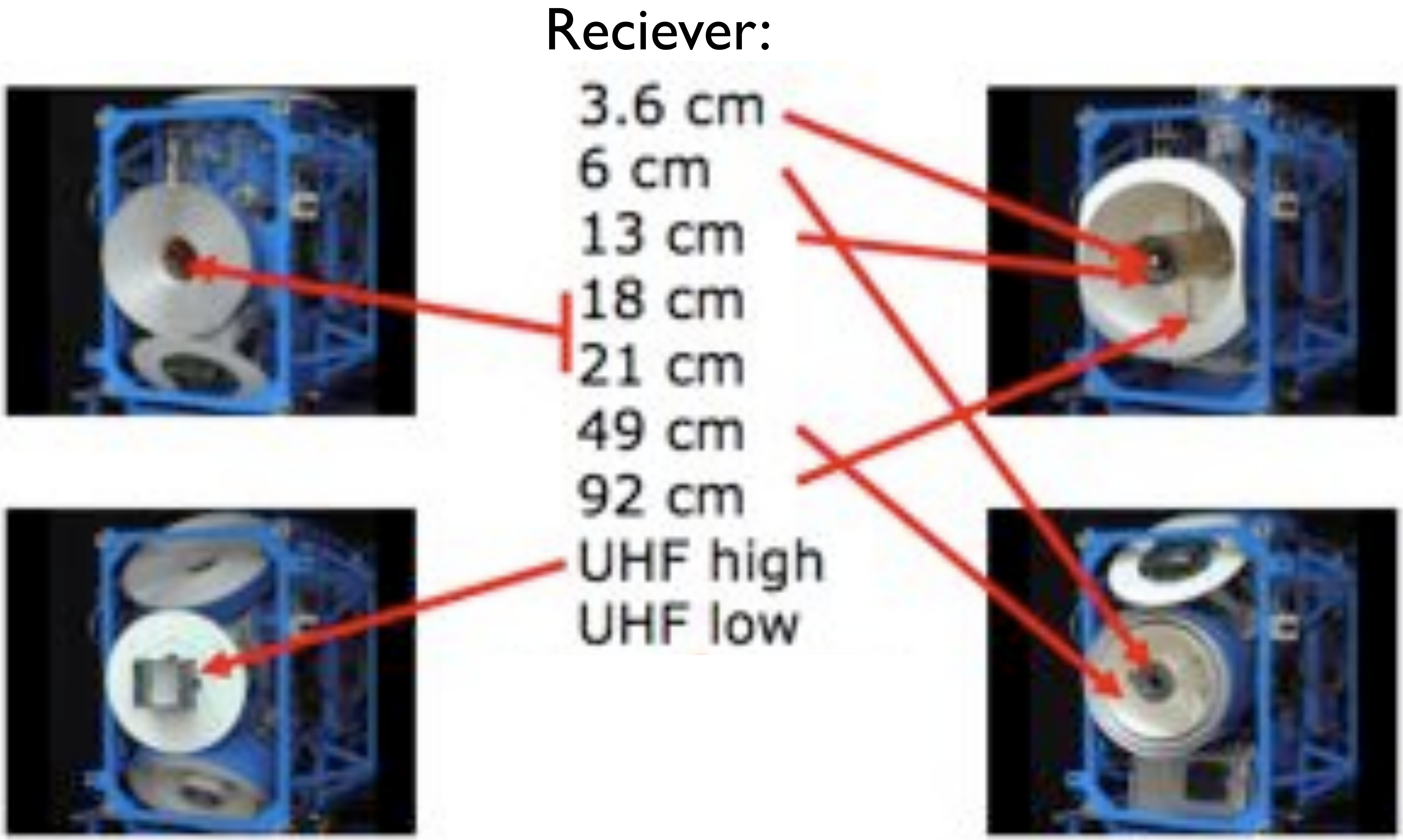


Fig. 6-9. Different aperture distributions with associated antenna patterns

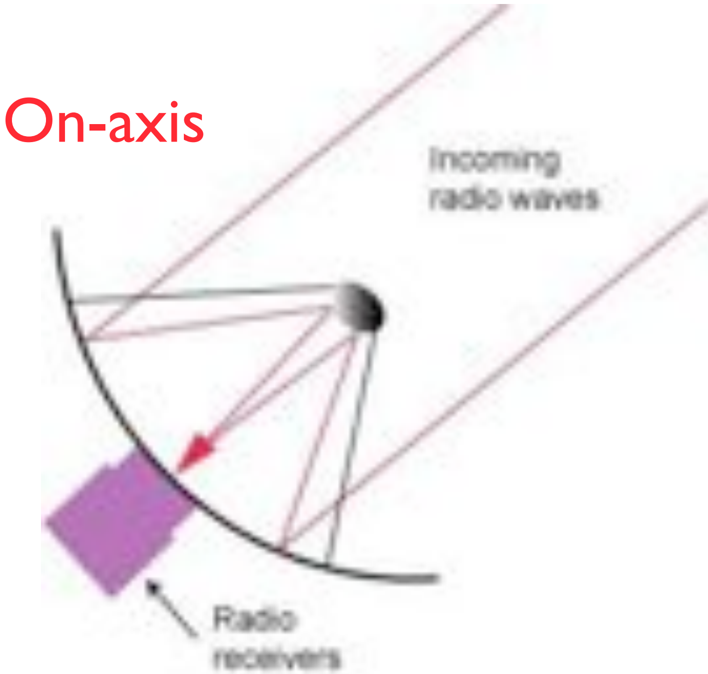
WSRT Multi-frequency front end (MFFE) system (lower wavelengths ==> larger feed - see eqn 13):



The VLA uses a rotating turret to position each of its feeds (receivers) slightly off-axis. Leads to some calibration problems.

Gregorian Receiver Room

On-axis



Off axis