Antenna Basics

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Introduction and Overview

- Radio antennas come in a great variety of forms.
- We will only consider a small number that are relevant to radio telescopes and radio astronomy in general.
- Starting from the simplest, we will deal with commonly used antennas and end with the antenna that is widely used in radio astronomy, the parabolic reflector.

Important Concepts

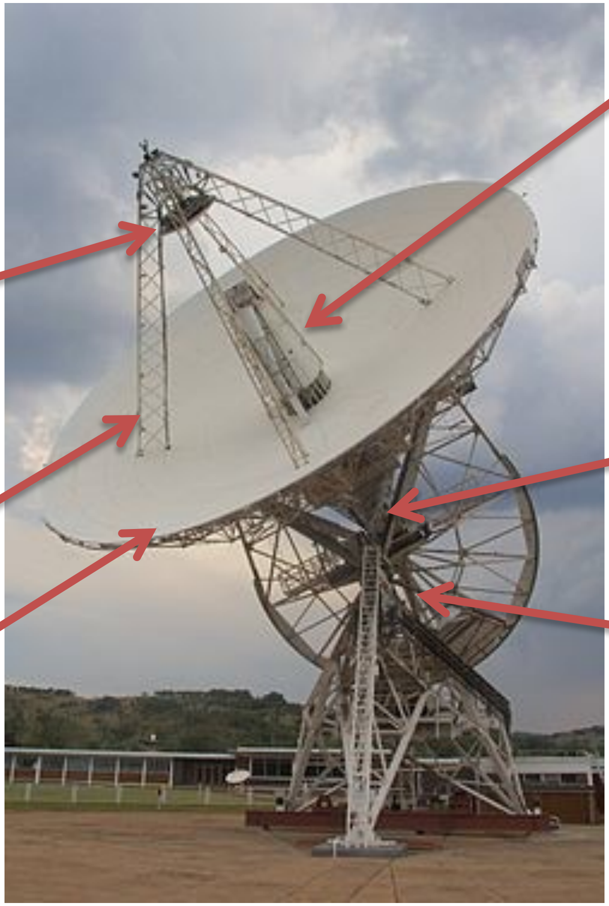
- A basic and important concept used when studying antennas is that of ***reciprocity***.

- What this means is that the properties of an antenna are the same whether it receives or transmits radio waves.

- Sometimes it is convenient to consider the antenna as a radiator – emitting or transmitting radio waves. When it receives, it then has the identical properties as when it transmits, and vice versa.

Components of a Radio Antenna

e.g. The **HartRAO 26m telescope => equatorially mounted Cassegrain** radio telescope



The **antenna reflectors** concentrate incoming E-M radiation into the focal point of the antenna

Secondary reflector or Sub-reflector (small reflector of hyperbolic curvature in front of the focus of the main reflector

Sub-reflector support legs

Primary reflector

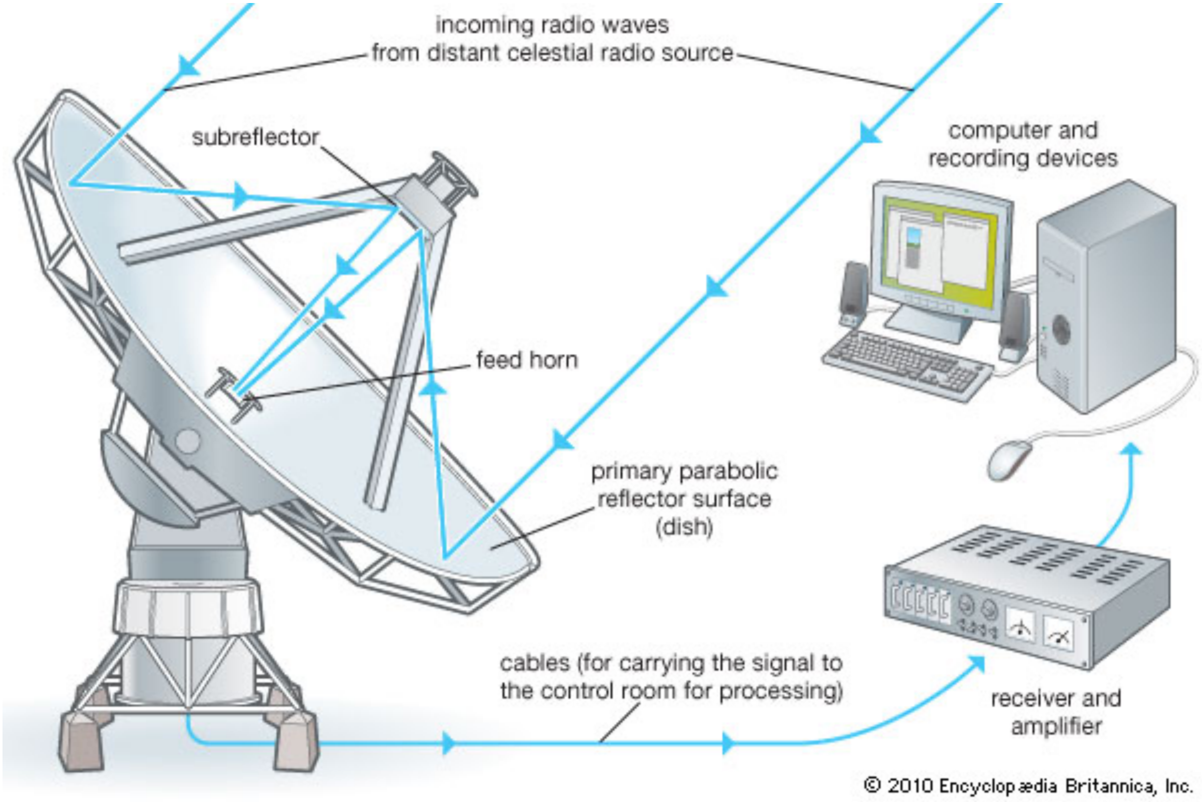
Feed housing (feed horns, receivers, and support structure)

Converts E-M radiation in free space to electrical currents in a conductor

Deck Room (Local oscillator and mixers)

Antenna positioner (points the antenna at the desired location in the sky)

Radio Astronomy Process



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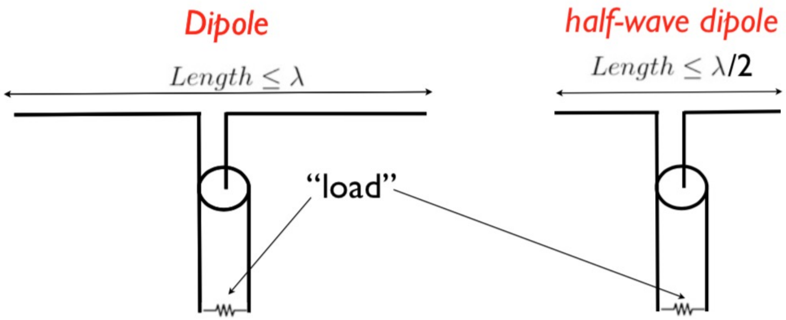
Radio Telescopes consist of (1) reflector, (2) antenna (feed) and (3) receiver

The Dipole Antenna



The dipole antenna is the basic antenna element.

When it transmits, it radiates energy in the form of a torus or doughnut, referred to as the ***radiation pattern***.

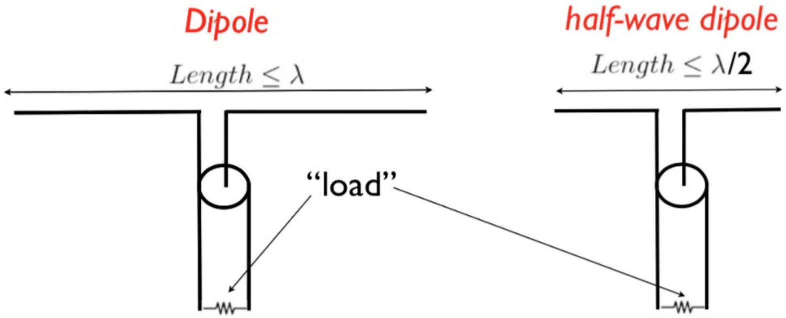
In a two-dimensional plane it projects as a double-lobed pattern

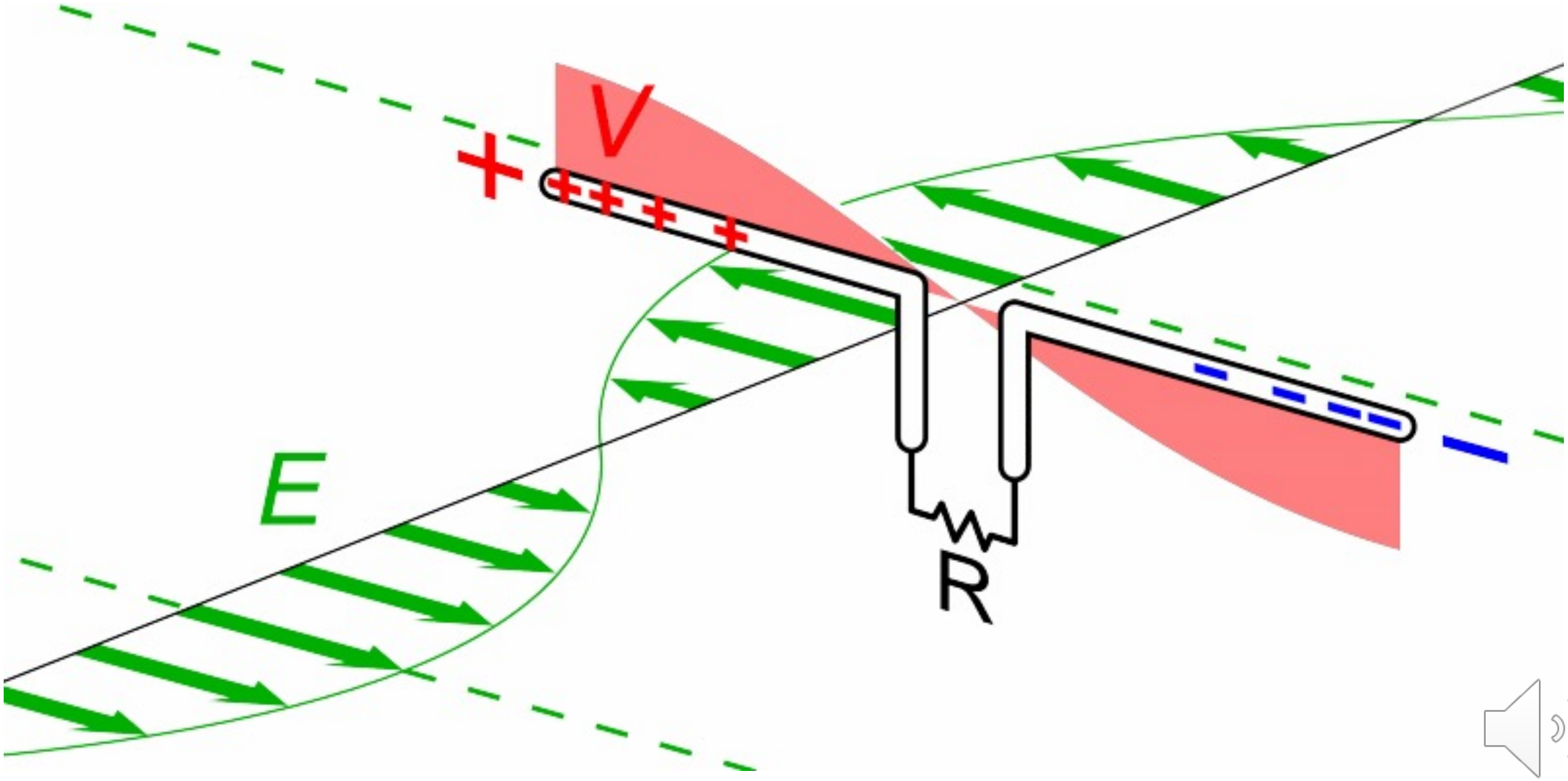
E-field of incoming radiation sets up currents in the antenna ==> voltages can be measured across a resistor (V = I*R).

Dipole length must be kept short, usually half a wavelength ($\lambda/2$) long.

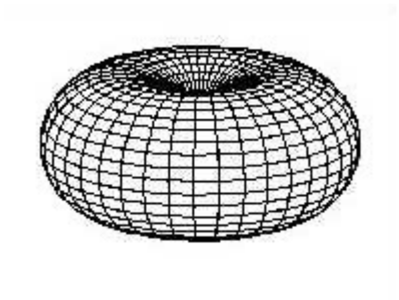
Any antenna is only sensitive to one polarisation (current is induced by a field that is p llel to dipole length).

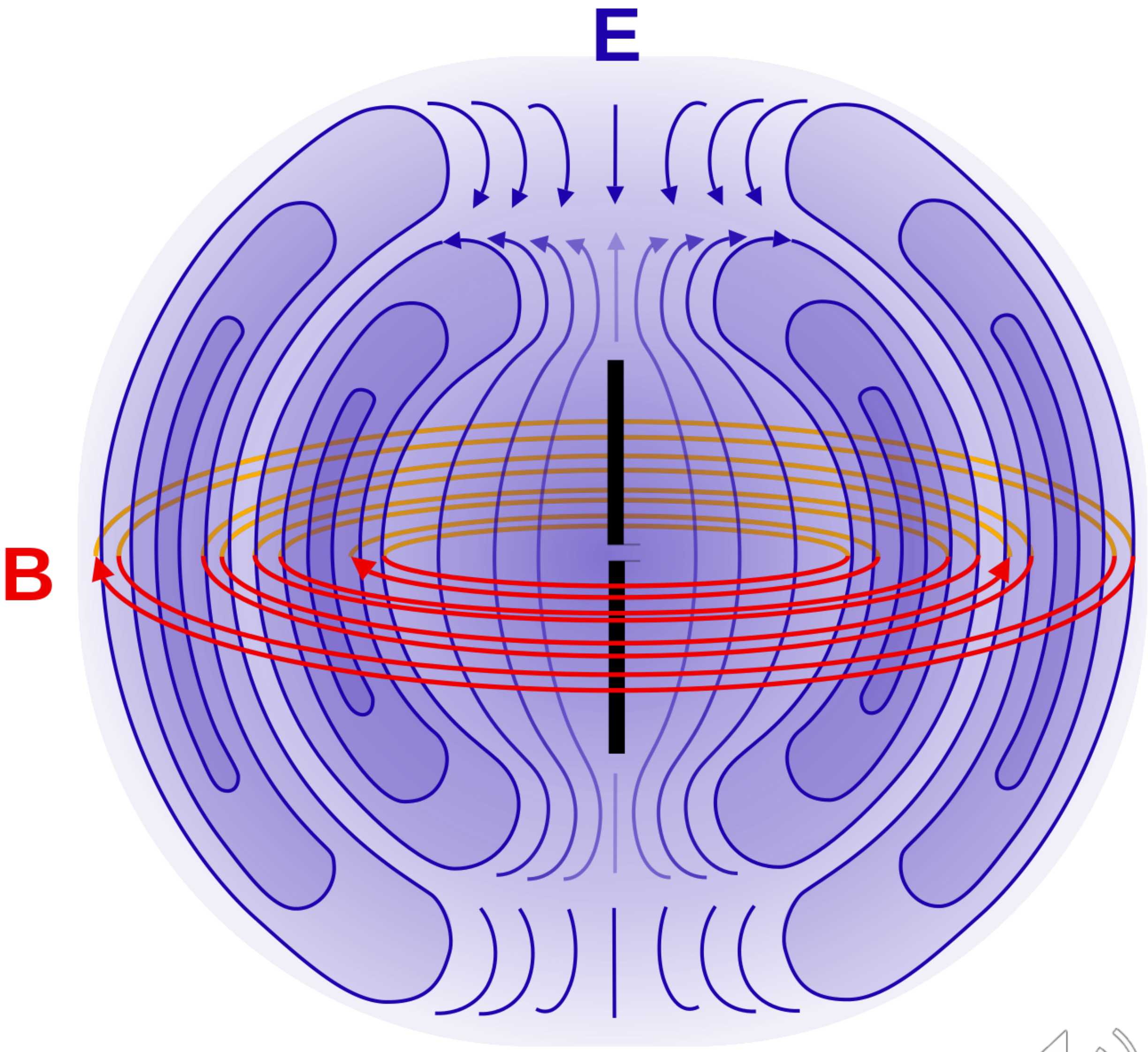
The Dipole Antenna





The Dipole Antenna





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.


Yagi


Helix


Log-periodic antenna

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


Dipole array

Pulsars Discovered Using Dipole Array

Jocelyn Bell and the telescope that she helped build!

2048 81.5 MHz λ/2 antennae
(16 E-W rows of 64 + 64),
1000+ wooden posts,
120 miles/192 km wire and cable.

57 tennis courts

Phased interferometric array

2 years to build

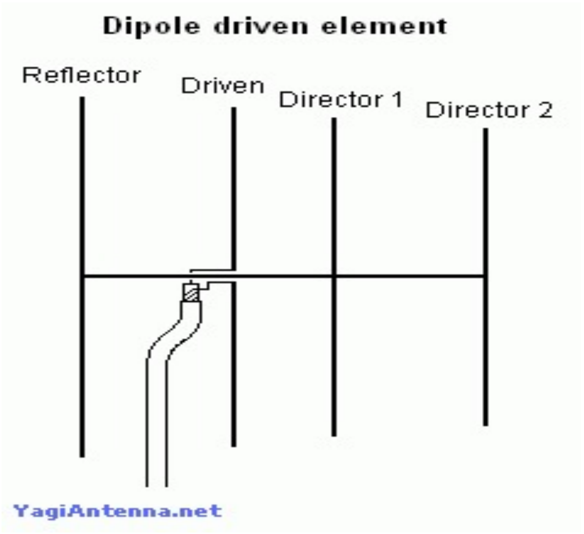
The Yagi Antenna

If one places a second slightly longer rod behind the dipole it acts as a reflector.

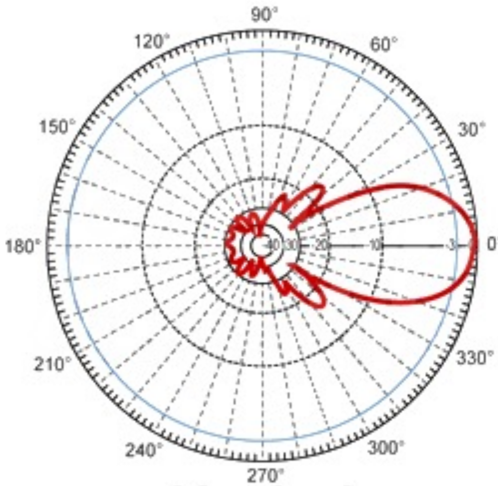
Increasingly smaller rods at appropriate distances in front of the dipole act as directors.

The net effect is to direct the radiation in the forward direction, making the antenna ***directional***.

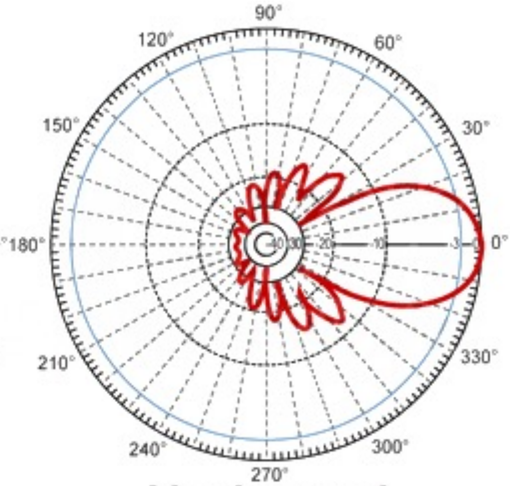
The ***principal, or main lobe*** points forward, with radiation in subsidiary directions via ***side lobes***.



YagiAntenna.net



Vertical



Horizontal

Some Basic Definitions

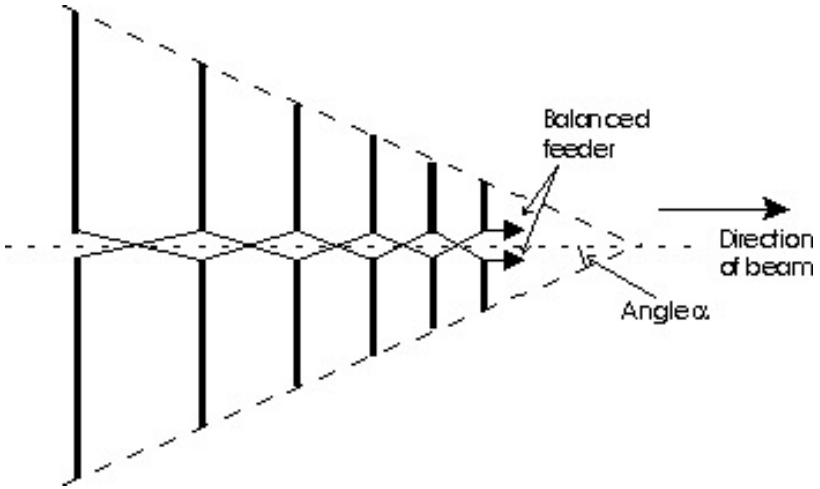
- Another important consideration is the range of frequencies over which an antenna radiates or receives.
- This is called the ***bandwidth*** of the antenna and is denoted by the symbol ***B***.
- This is defined as ***B = f2 – f1*** where:
  f1 is the lower operating frequency and
  f2 is the upper operating frequency.
- Dipoles and Yagis have a small fractional bandwidth ***B/fo*** (where ***fo*** is the centre frequency) of about a few percent, although there are methods of increasing this.

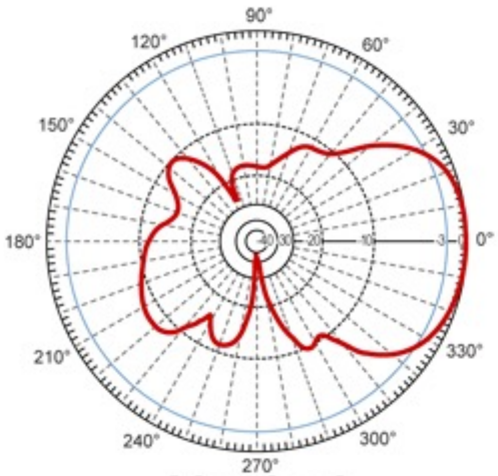
The Log-Periodic Antenna

Logarithmic-periodic antennas are a variation of the dipole and Yagi antennas. They consist of a series of dipole elements of increasing size, with a logarithmic progression of spacing.

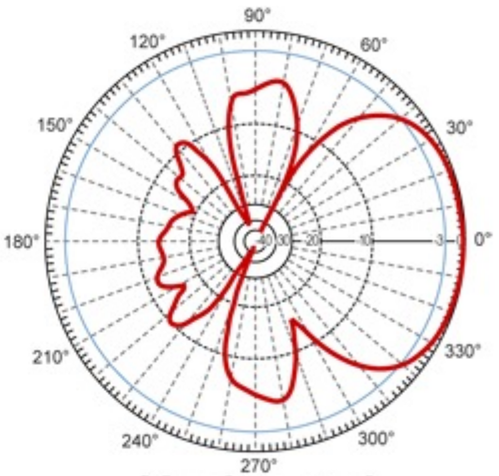
This gives the log-periodic antenna a far greater ***bandwith***, which enables if to operate over a wide range of frequencies. For these antennas, ***f2/f1*** **can be as large as 20**.

Typical radiation patterns for a log periodic antenna are show on right and are roughly independent of frequency.





Vertical



Horizontal

Antenna Gain

- At this point it is convenient to introduce the concept of ***antenna gain***.
- We define an ideal ***isotropic antenna*** as one that radiates or receives equally in all directions.
- The ***gain*** of a given antenna is then the ***ratio*** of the power received by an antenna from a transmitter, to the power received by an ideal isotropic antenna.
- Gain is measured in decibels (***dB***), defined as ***dB ratio = 10 x log (P2/P1)*** where ***P2*** is the power received by the given antenna and ***P1*** is the power received by the ideal isotropic antenna.

Aside: Power Ratios

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:

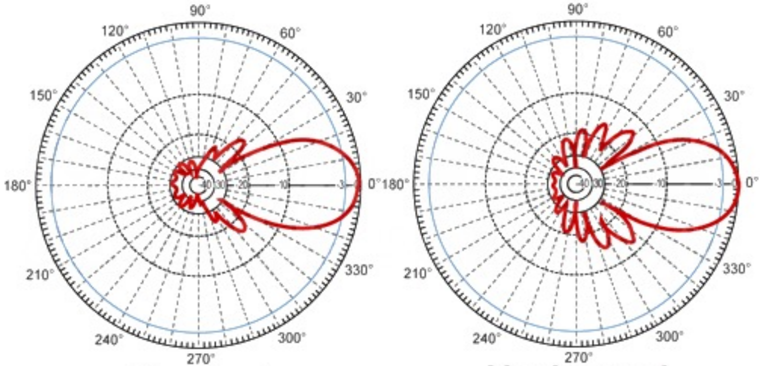
$$Power_{dBm} = 10\log(\frac{P}{mWatt})$$

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 Beamwidth



Vertical

Horizontal

The main lobe of the antenna pattern is also balled the ***main beam***.

The angular distance between the directions at which the power falls to one half its value in the centre defines the ***half-power beamwidth***, contracted to ***HPBW***.

For the radiation patterns shown, the radial scale is in decibels, shown in circles at 3 dB, 10 dB, 20 dB, 30 dB and 40 dB.

On a dB scale, the HPBW is measured at the 3 dB point on the beam, shown by the blue circle.

The minimum between the main lobe and the first side lobe is known as the first null, and those between successive sidelobes as the 2nd, 3rd, 4th, … nulls.

Antennas Used as Radio Telescopes

- The most common antenna used as a radio telescope is the parabolic reflector.

- The main reason for using these is that they are frequency independent, and within certain constraints can be used at any frequency.

- This makes them very versatile, but they generally require separate receivers for each frequency band at which they operate.

The Parabolic Reflector

The basic parameters of a parabolic reflector are:

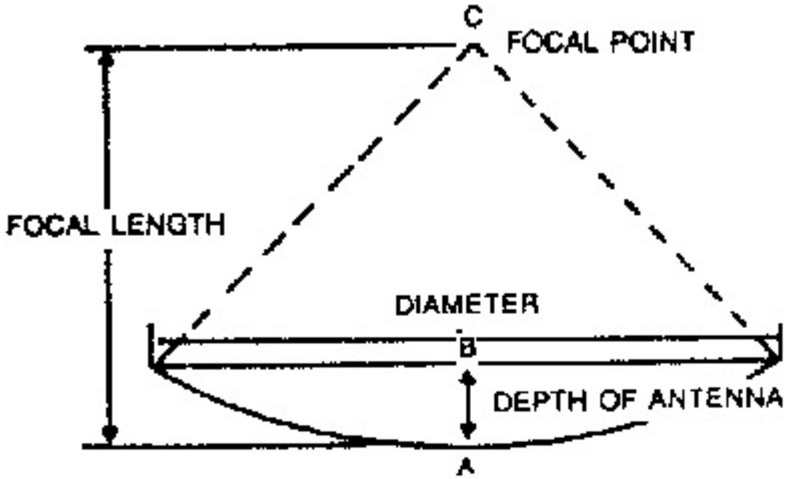
Diameter: D
Focal length: f

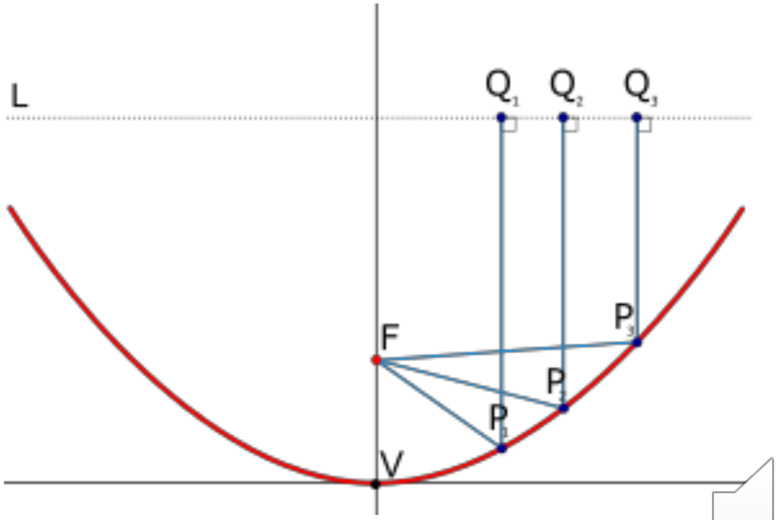
The ratio f/D, called the focal ratio, is a measure of the depth of the paraboloid.

Important properties:

Rays radiating from the focus are reflected as parallel rays. The distance travelled by any ray from the focus to a fixed line, L, parallel to the aperture of the parabola, is always constant.

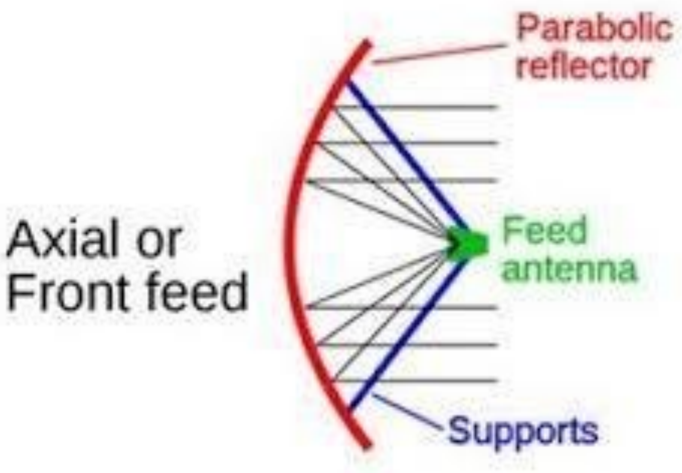
Therefore, the wavefront normal to the exiting rays always has a constant phase.





Feeds

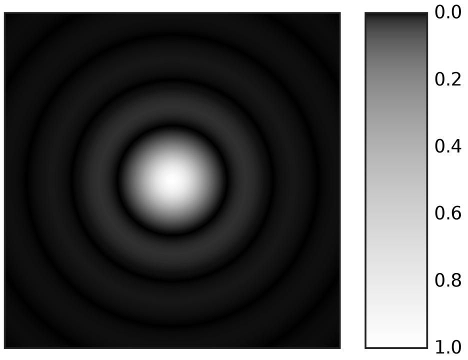
The feed antenna, often contracted to ***the feed***, must have a radiation pattern that correctly illuminates the paraboloid, without spilling over the edges – lost energy is known as ***spillover***.



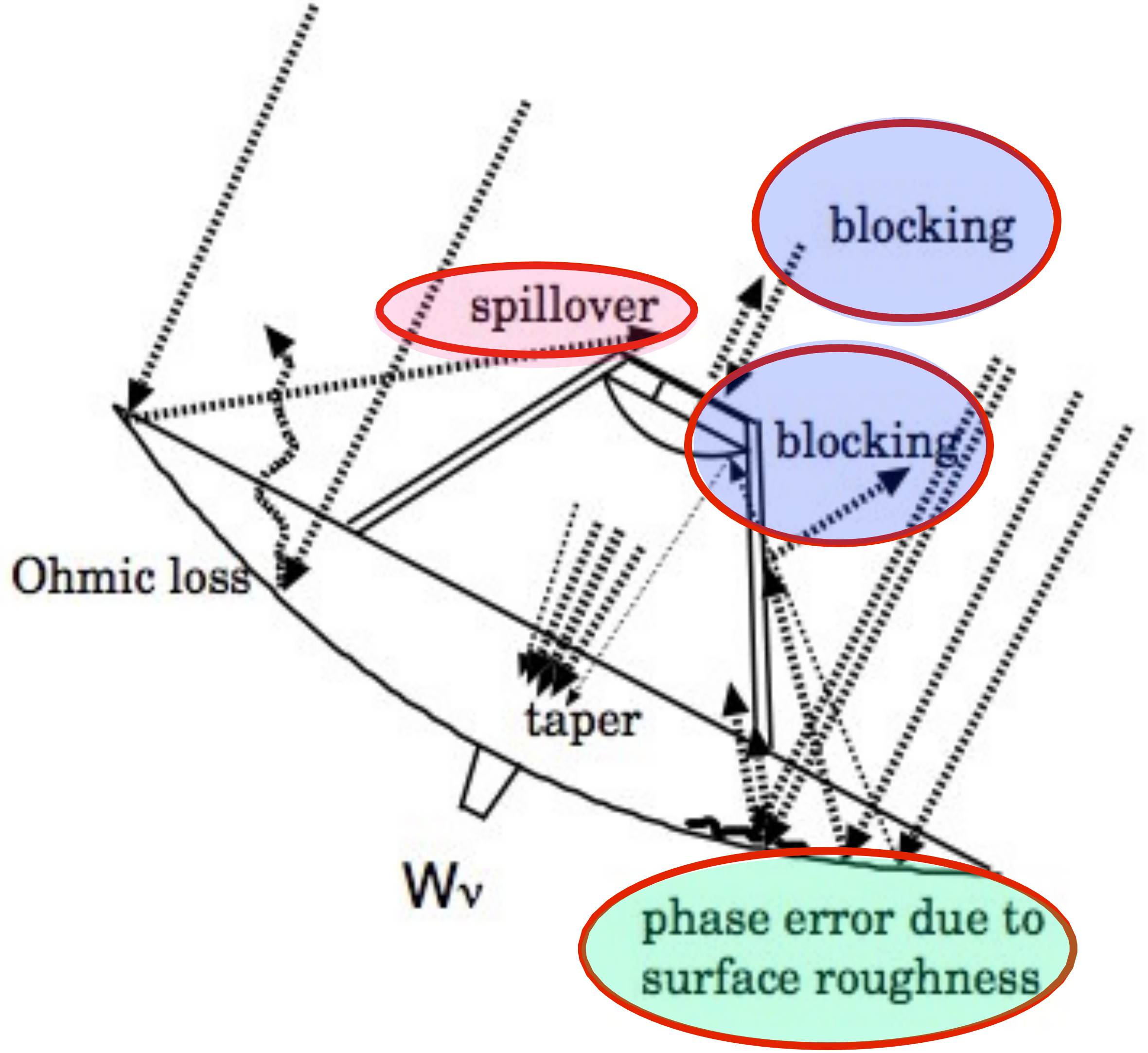
For a front fed prime focus feed, a horn feed is most commonly used.

Because the wavelength is not that small, the energy received at the focus is not confined to a point, but fills a small circle at the focus, known as the ***Airey disc***, with a diameter proportional to the wavelength.

The aperture of the horn must then be matched to the Airey disc for it to intercept the maximum amount of energy.

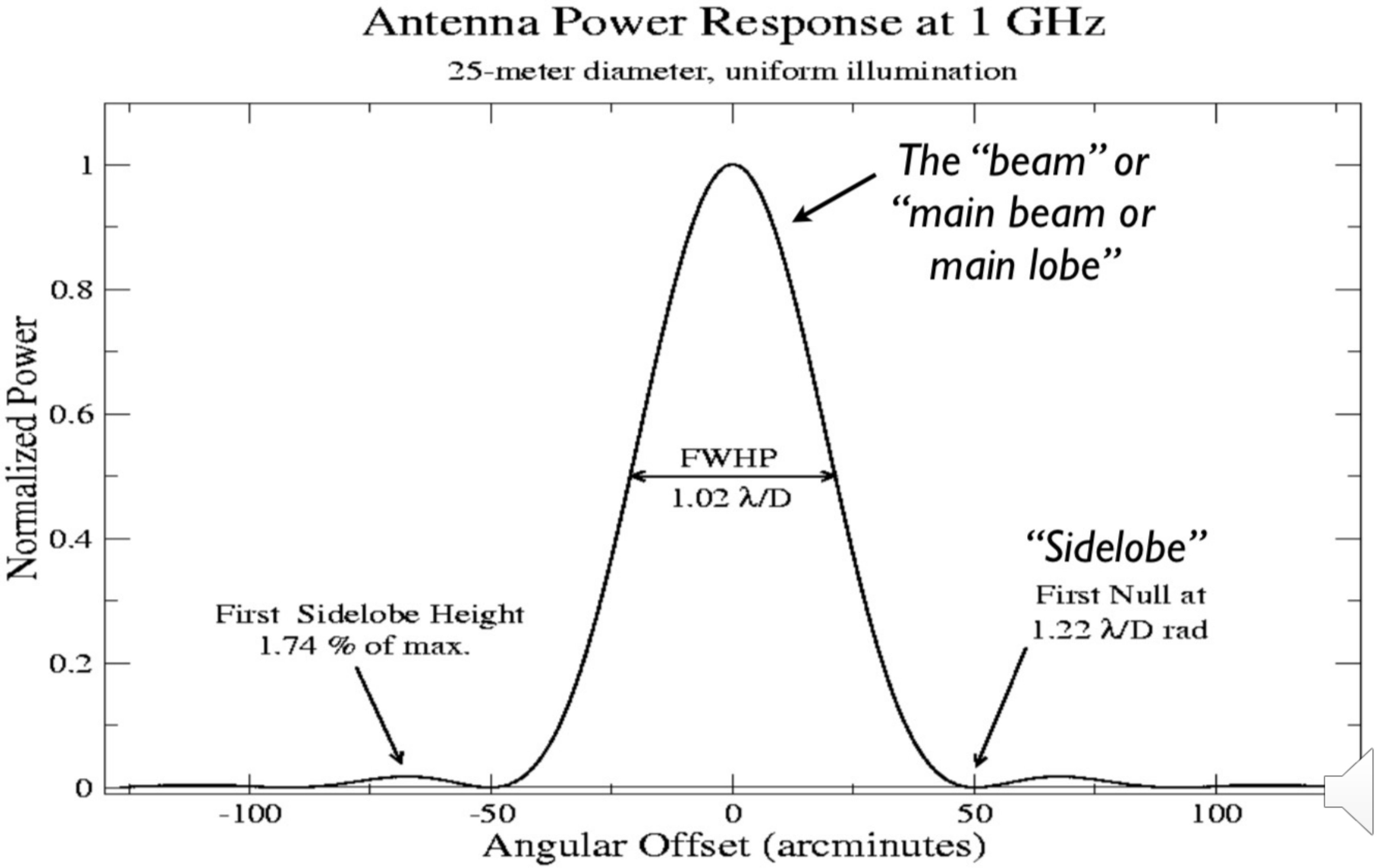


Illumination



Power Beam Pattern

The response of a uniformly illuminated circular parabolic antenna of 25-metre diameter, at a frequency of 1 GHz (or imagine the telescope response if transmitting...)

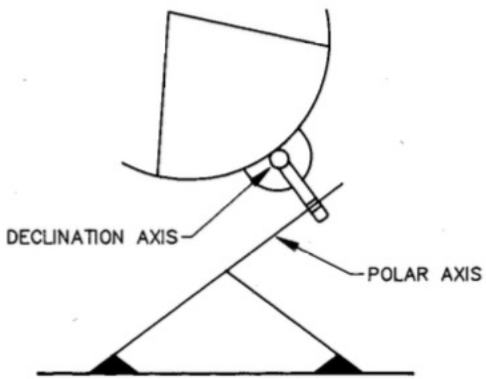


The "beam" or "main beam or main lobe"

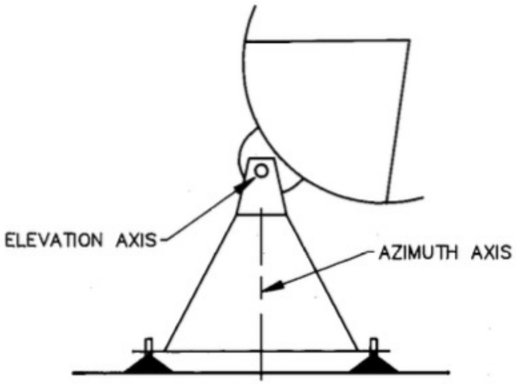
"Sidelobe"

Types of Mounts

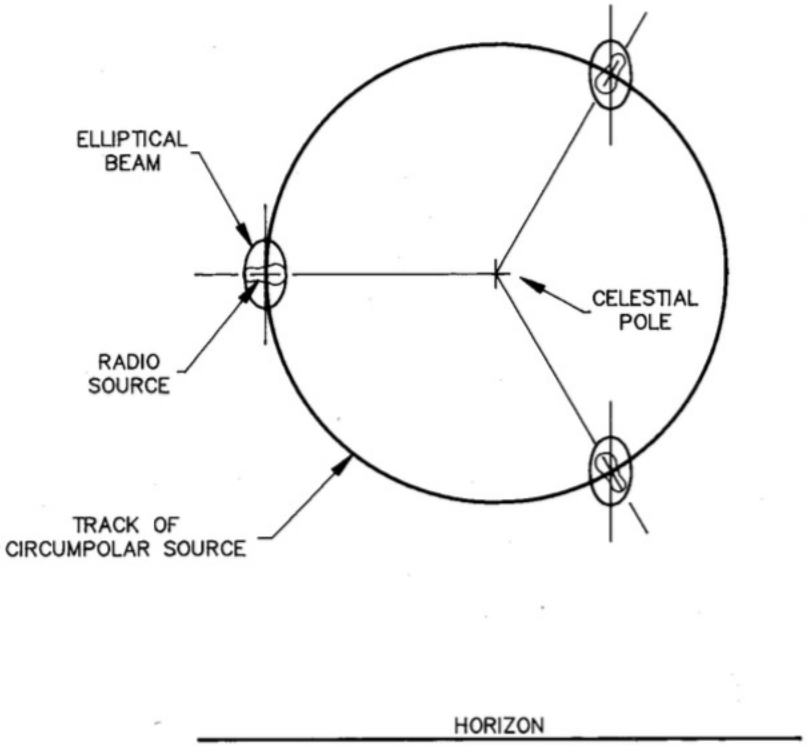
Different types of mount: Modern antennas are mostly ***alt-az* (rotates around 2 axes)** because they are cheaper to build and well-balanced mechanically (important for large, heavy telescopes).



EQUATORIAL MOUNT

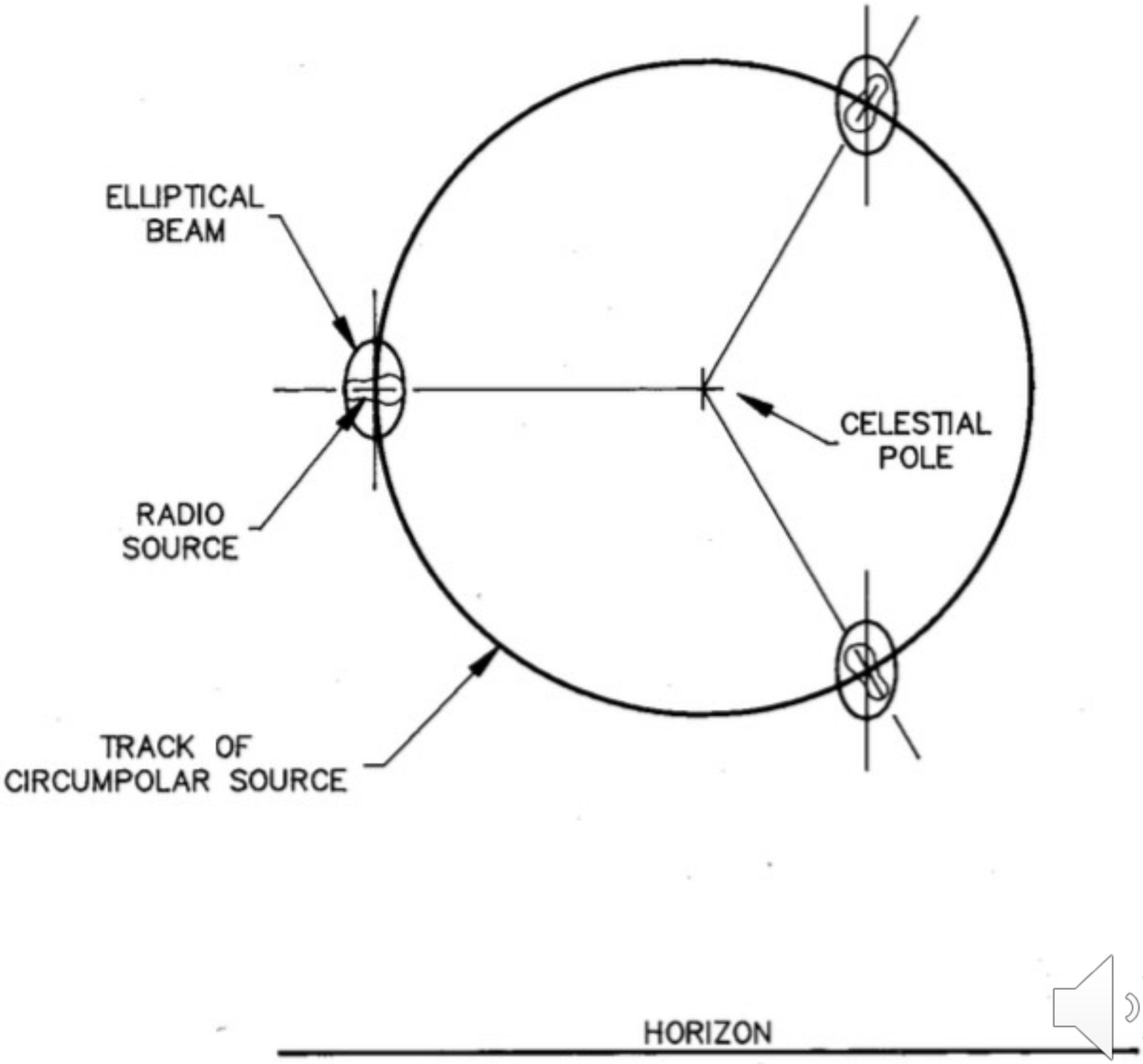


ALTITUDE OVER AZIMUTH MOUNT



- ***Polar mounts*** rotate around 1 axis.
- One disadvantage of polar mounts is that you can only track a source for 12 hours.
- Another disadvantage is you need to use heavy counterweights.
- Disadvantage of ***alt-az telescopes*** is that the orientation of the telescope beam changes (rotates) as the source moves across the sky (see next).
- This needs to be corrected in software, e.g., for polarisation measurements.

Field Rotation



Polar Telescope with Large Counterweight

Westerbork Array
in the Netherlands

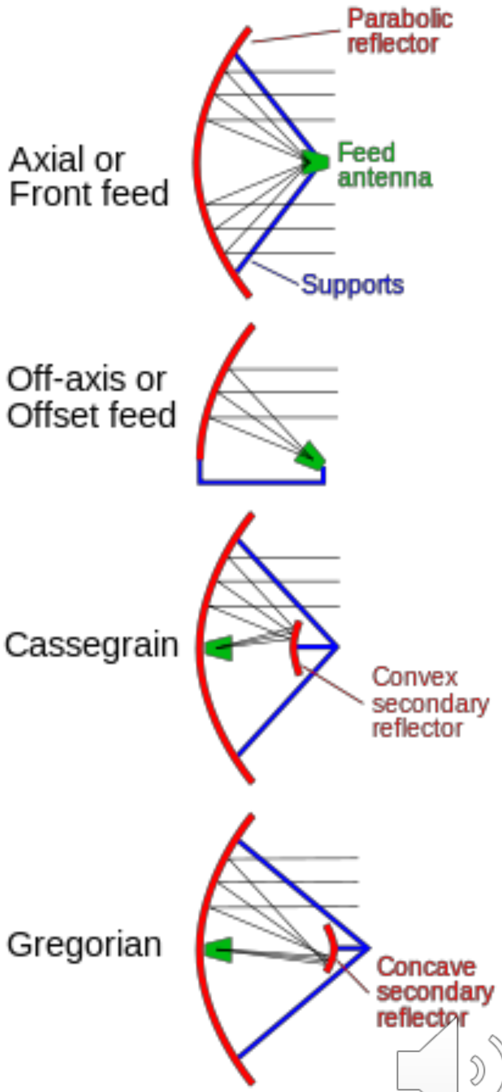
Reflector Types

The axial or front-fed feed is the most basic, and is known as a ***prime-focus feed.***

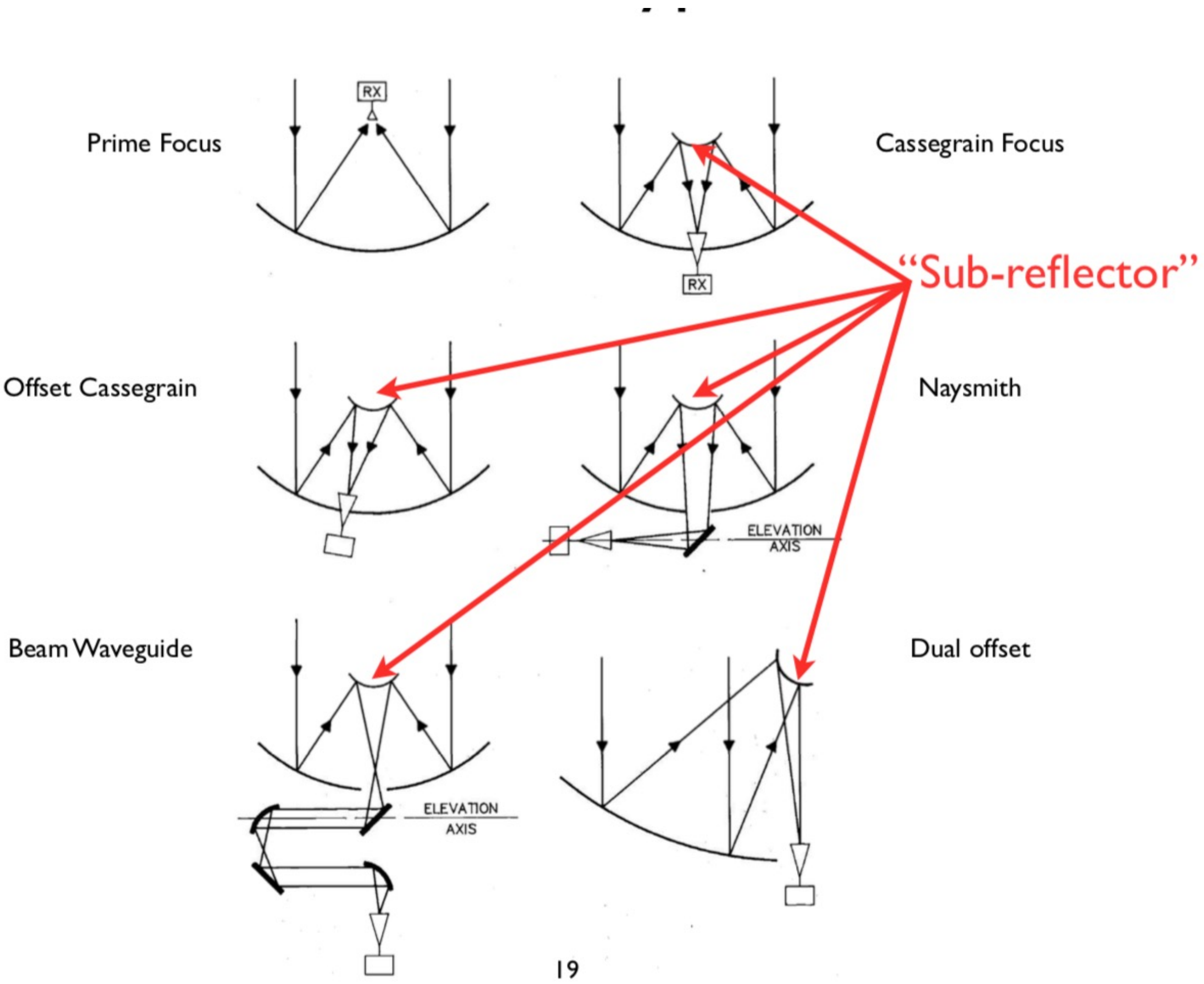
The most common use of the ***off-axis or offset feed*** is for TV satellite reception. It has a clear aperture with no blockage loss.

The ***Cassegrain feed*** is widely used for radio telescopes and large satellite communication antennas. The secondary reflector is ***hyperboloidal*** in shape and is below the primary focus. It generally has high efficiency, and low spillover towards the ground.

The ***Gregorian feed*** is similar to the Cassegrain, but the secondary, which is ***ellipsoidal*** in shape, lies above the prime focus. Similar advantages to the Cassegrain, but an additional one is that prime focus is accesible without removing the secondary reflector.



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. SKA, GBT,
ATA

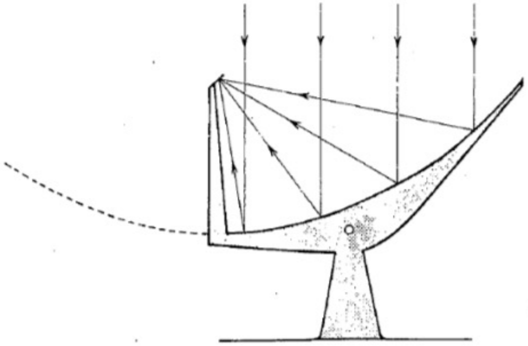
Offset Antennas have no blockage and a “cleaner” beam compared to prime focus, Cassegrain, etc.

Reflector Types

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 asymmetry of the offset optics introduces nasty polarisation characteristics that can limit imaging results.



Offset "high" Gregorians (left & above) have no blockage of the aperture. A good example of this system includes the largest steerable telescope in the world: the Green Bank Telescope (GBT).

Offset "low" Gregorians have better access to receivers see MeerKAT dishes on next slide.

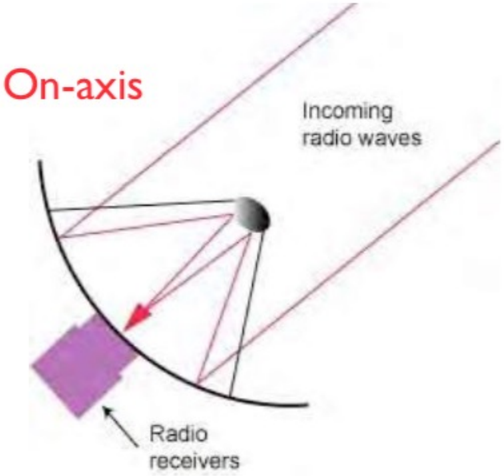
MeerKAT Dishes

Reflector Types

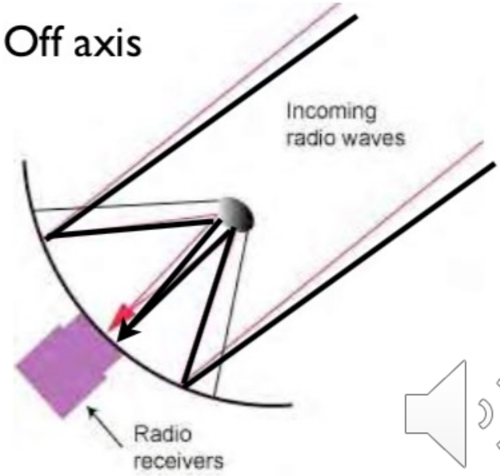
The VLA uses a rotating turret to position each of its feeds (receivers) slightly off-axis. This leads to some calibration problems.

Gregorian Receiver Room

On-axis



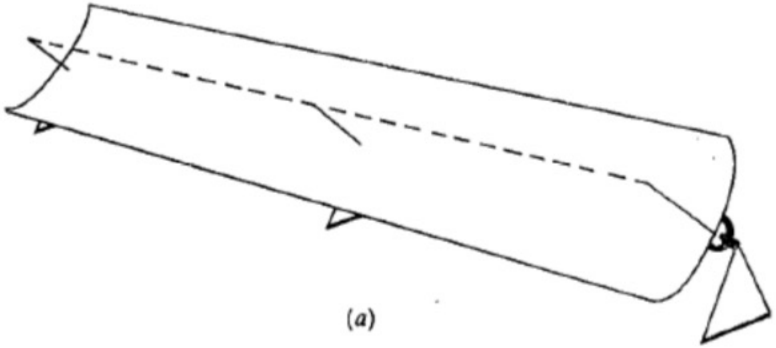
Off axis



Some Other Approaches...

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). Cylinders are cheaper to build than paraboloids but have non-symmetrical beam patterns.



Other Similar Examples

RATAN 600 - Russia

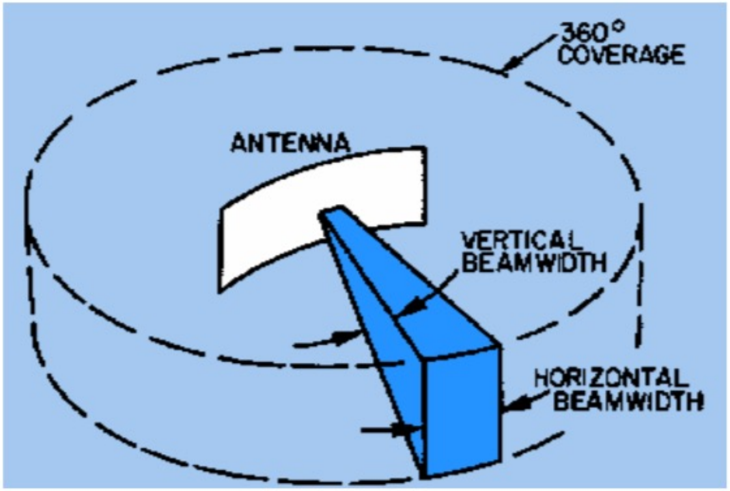
Nancay - France

Cross Antenna

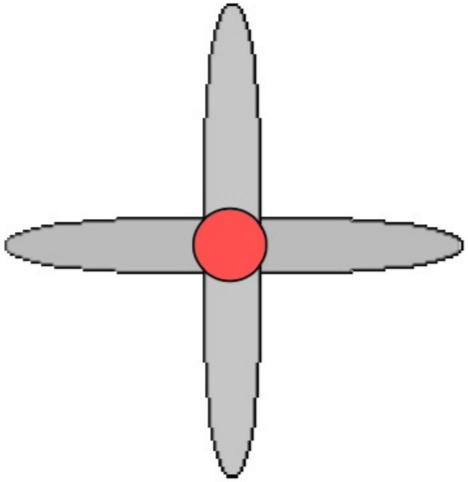
Instead of building an entire parabola, Cross Antennas employ two narrow sections of a parabola, that are perpendicular to each other.

Individually, each section provides a beam that is narrow in the antenna's wide direction, and broad in the other direction: .

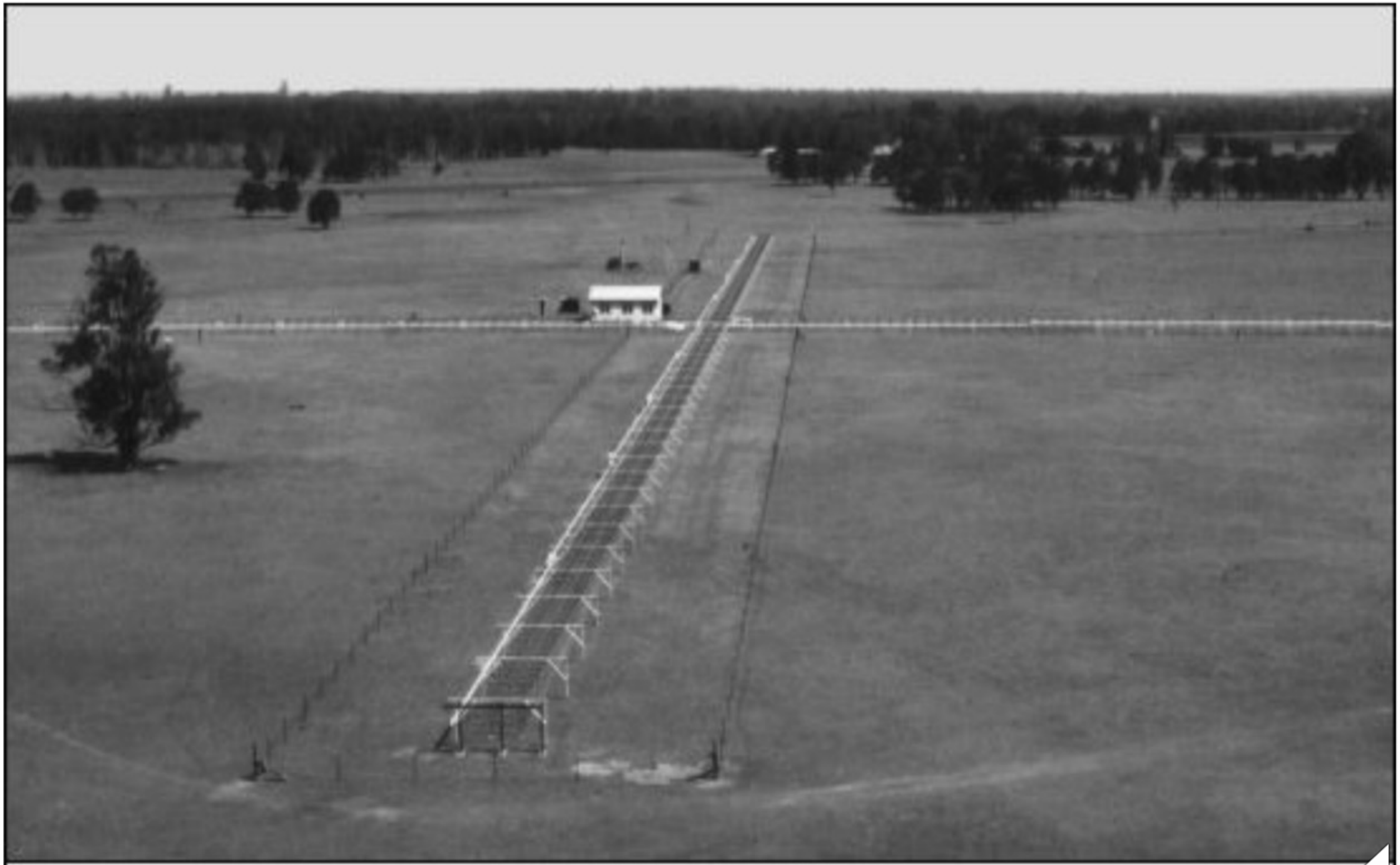
By observing a source with two orthogonal beams, we can get a 2-d image of the sky.



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



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



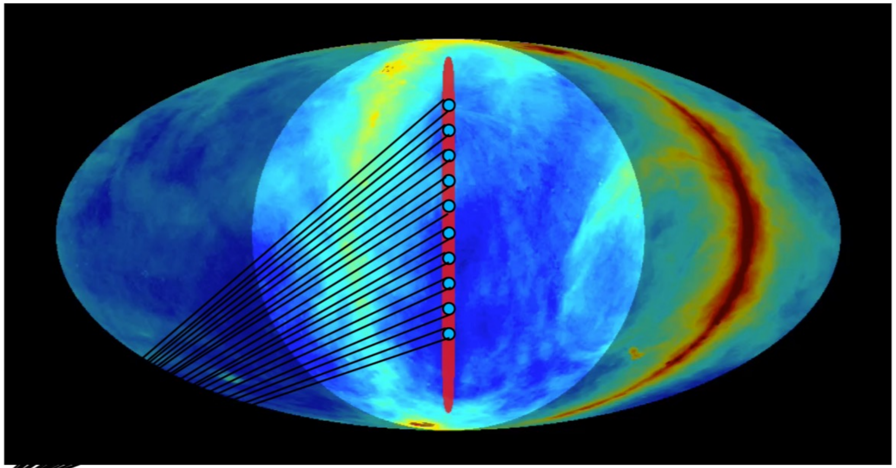
MILLS CROSS (CSIRO)

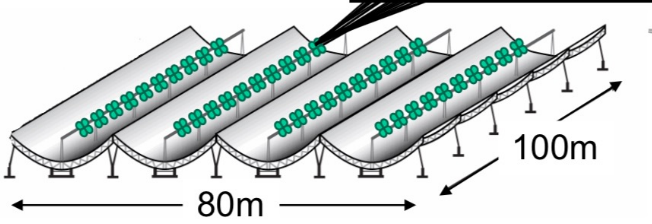
Many other examples:

Not Just Old Telescopes… CHIME

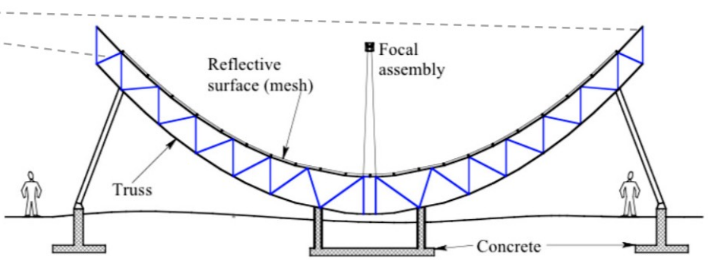
Ng et al 2017

10 tied-array beams
for CHIME/Pulsar





4 Cylindrical reflectors
No moving parts



1024
feeds

Receiver
huts

Power
supply

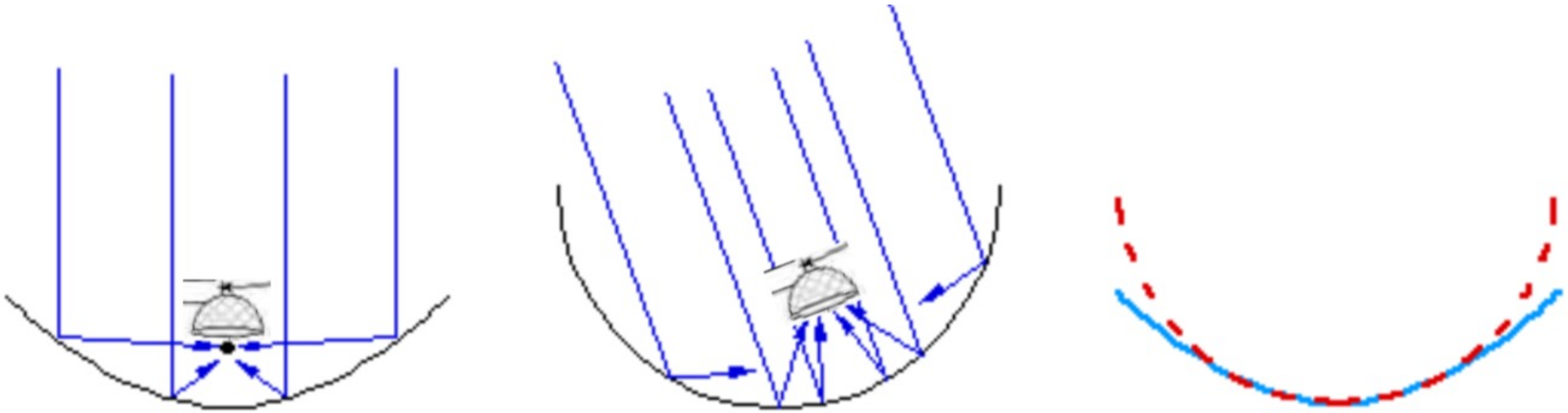
Single Fixed Large Dishes

Arecibo – Puerto Rico – 300m

FAST – China – 500m!

Single Fixed Large Dishes

While a parabola has a single focus point, a ***spherical reflector*** like Arecibo/FAST focuses the incoming radio waves in a line:



Parabolic: Perfectly focuses parallel rays, but from one direction only. (Must be aimed.)

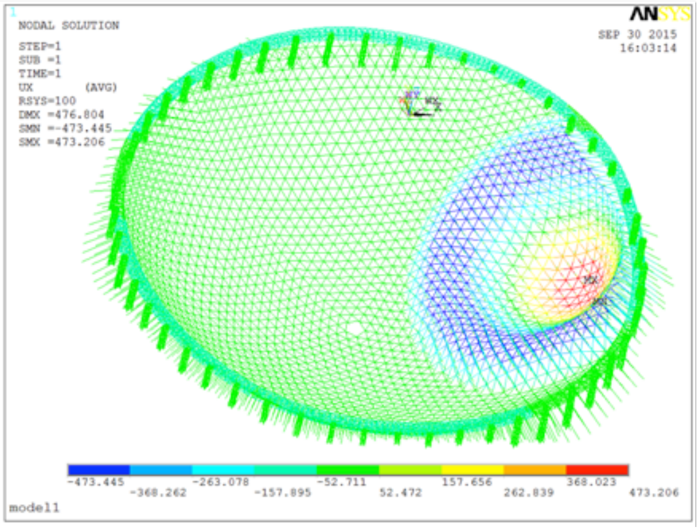
Spherical: Focuses imperfectly, but equally well from any direction. (Does not need to be aimed.)

Together: The circle of curvature (red) nearly coincides wih the parabola (blue) near the vertex.

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 - for Arecibo /FAST the effective parabolic area typically available is about 2/3 of the physical area.

FAST Has an Active Surface…



```
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
UX        (AVG)
RSYS=100
DMX =476.804
SMN =-473.445
SMX =473.206
```

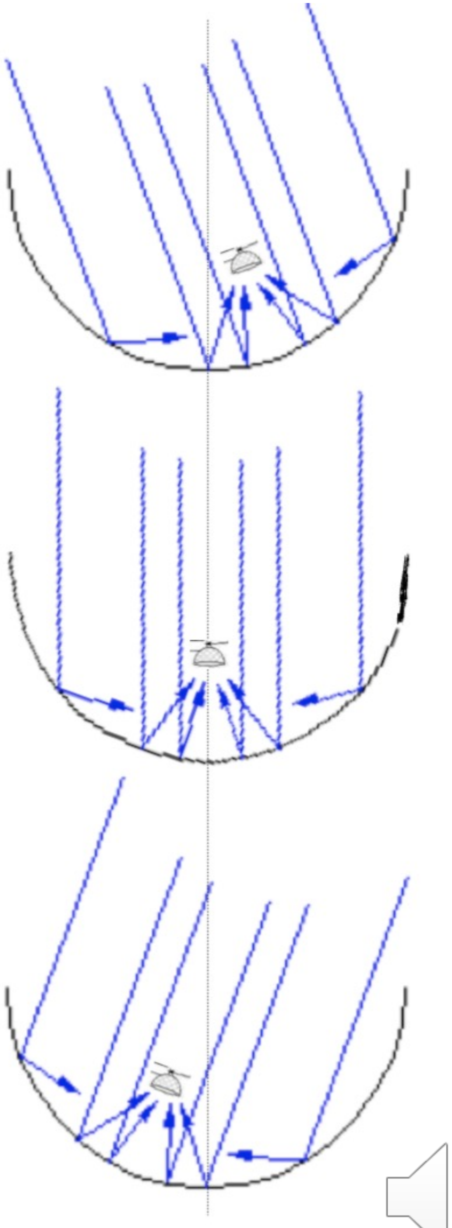
Limited Range of Sky

Moving the sub-reflector laterally across the focal line, permits a wider (but still restricted) field of view to be observed.

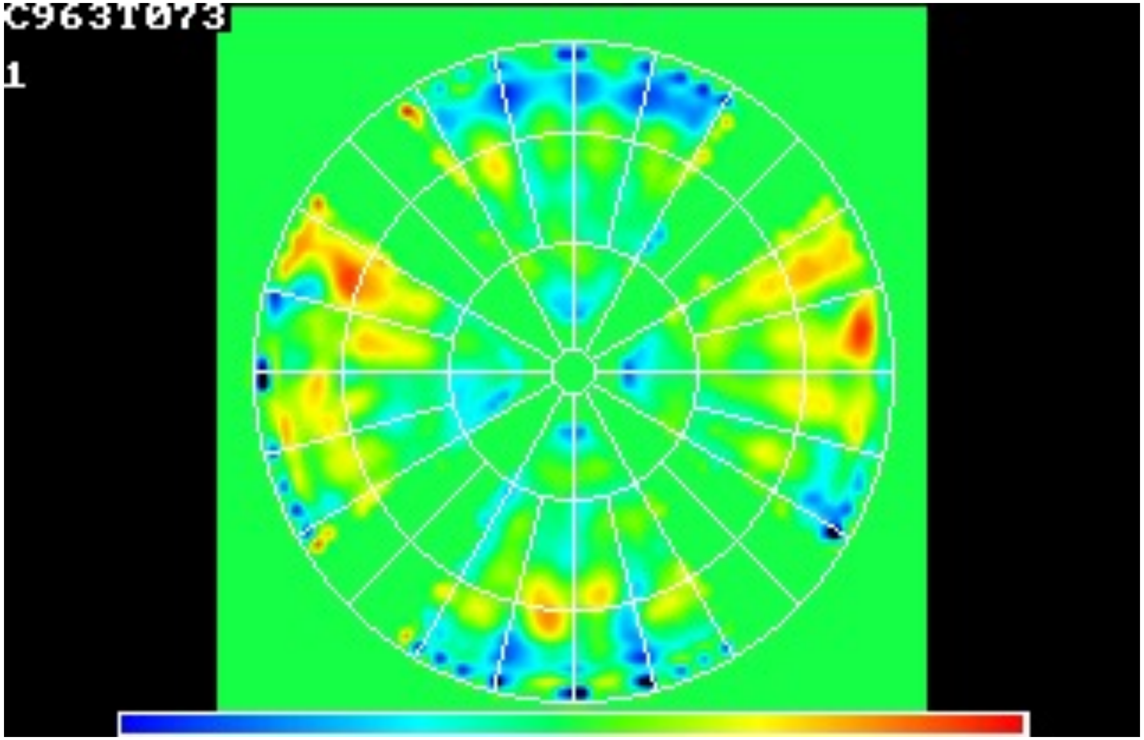
Typically, FAST can track a specific source for 2-3 hours.

Arecibo’s DEC range was restricted to -1º to +35º.

FAST’s larger size and active surface allows sky coverage with a DEC range of -14º to 66º (-1º to 52º with full gain).



Limitations



The first limitation is the diameter measured in wavelengths, i.e., ***D/λ***, which must be > 15. For radio telescopes, D is generally much greater than λ, e.g., λ = 1.3 - 13 cm, D = 26 m, D/λ = 200 – 2000.

The second limitation is the deviation from true paraboloidal shape, including distortions in individual panels as well as misalignment of individual panels. This is shown in the diagram, which maps errors in a dish surface measured with a technique known as radio holography.

Surface Accuracy

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

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

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

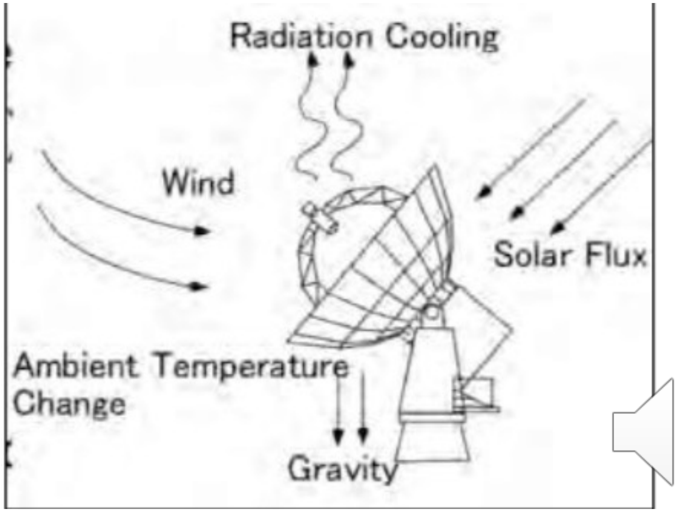
Re-arranging:

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

E.g., for a surface efficiency of 0.7 (typical minimum target value), the required surface error (r.m.s.) is ~λ/20.

==> at 7 mm (43 GHz) the surface accuracy must be ~ 350 micron. That's only ~twice the width of a human hair!

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



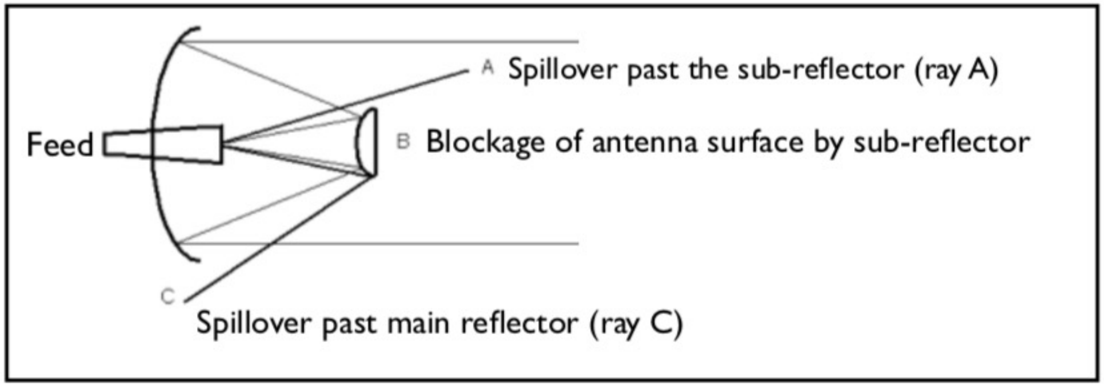
Antenna Performance

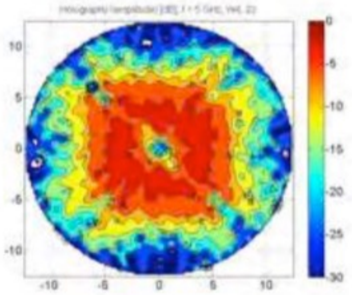
The antenna aperture efficiency $\eta = \dfrac{\text{Power collected by feed}}{\text{Power incident on antenna}} < 1$

There are many different potential loss factors: $\eta = \eta_{sf}\eta_{bl}\eta_{sp}\eta_{t}\eta_{misc}$

η ~ 0.65 <==

- Surface efficiency ~ 0.9
- Aperture blockage efficiency ~ 0.9
- Feed spillover efficiency ~ 0.9
- Feed illumination efficiency ~ 0.9
- Misc. - other minor losses e.g feed mis-match.



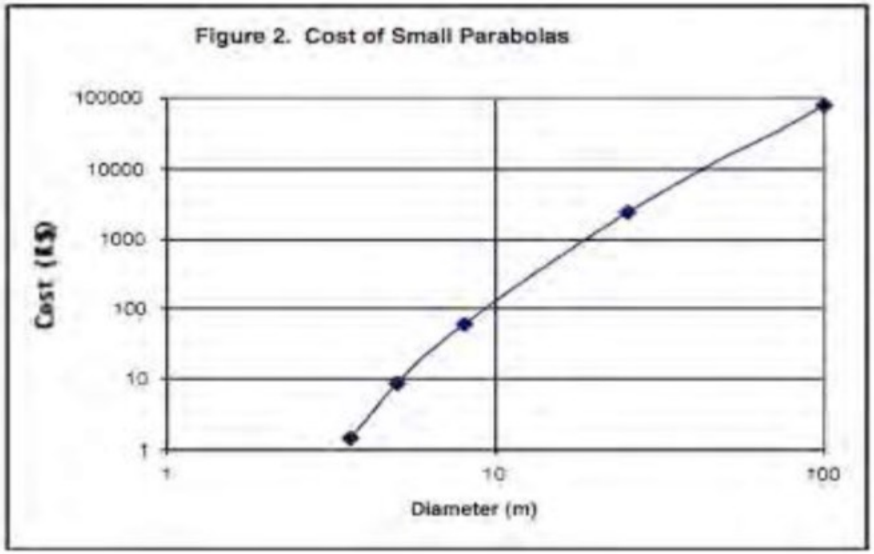


Feed does not illuminate all of antenna surface equally

How Big Can Parabolic Radio Telescopes Be?

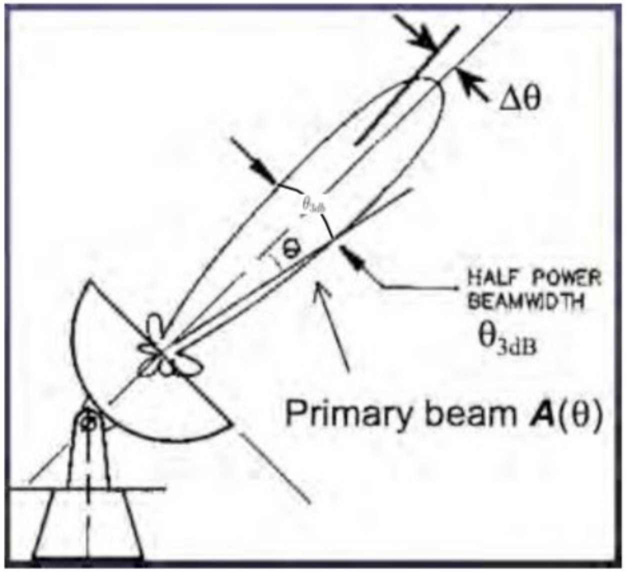
As the size (diameter) of a radio telescope increases, the gravitational and wind loads on the structure become difficult to manage. The worst problem is the problem of surviving a storm. The degree of wind distortion between paraboloids of different diameters (D) scales as D^3.

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!

Antenna Pointing Errors $\Delta\theta$



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).

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

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

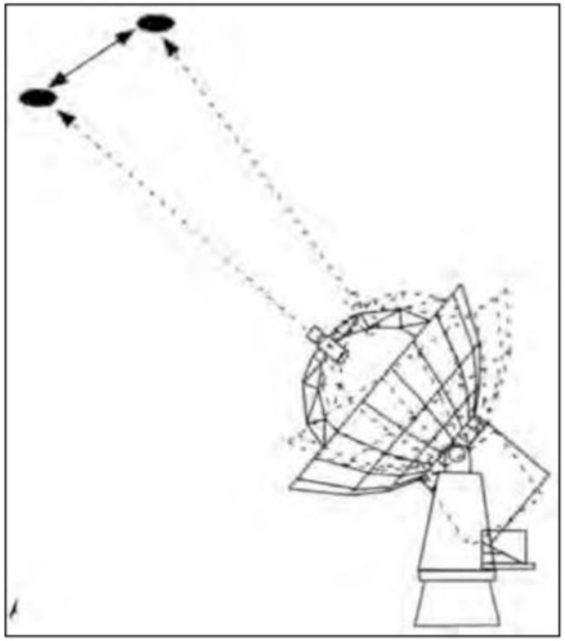
(ii) calibration (e.g. fast switching between nearby sources in the case of phase-referencing).

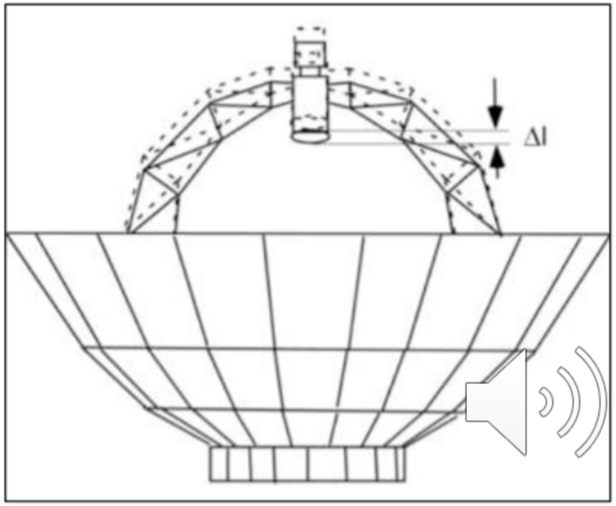
Typical driving rates of modern dish (e.g. VLBA):

- 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).





Antenna Gain and Performance

The ***flux density (S)*** is equal to the ***Planck function I(ν)*** (“specific intensity”), integrated over solid angle:

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

$$S = \int 2kT_b\nu^2/c^2 d\Omega = 2k\nu^2/c^2 \int T_b d\Omega$$

Above, we use the ***Rayleigh-Jeans law*** (the low-frequency approximation to Planck’s law) and see that the flux density of a source is just its brightness temperature (T_b) integrated over the source size.

If the T_b is uniform across the source, and the source size is equal to the beam size on the sky, the ***integrated flux density*** of the source is:

$$S = (2kT_b/\lambda^2)\ \Omega_a \quad [A]$$

where Ω_a is the solid angle of the beam.

The ***peak flux density*** is sometimes quoted in papers - this is measured in Jy per be or Jy/beam.

Antenna Gain and Performance

The angular response of a parabolic antenna with aperture size D, observing at a wavelength λ, is diffraction limited and focused into a cone. The solid angle of a cone (approximated for small θ) :

$$\Omega_A = \frac{\pi}{4}\theta^2 = \frac{\pi}{4}\frac{\lambda^2}{D^2} \sim \frac{\lambda^2}{D^2}$$

Note if we substitute this into [A] we get:

$$S = \frac{2kT}{\lambda^2}(\frac{\lambda}{D})^2 = 2KT/D^2 \quad \text{[B]}$$

Noting that the ***power (P) into the receiver*** is given by:

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

By equating with [B] we can write:

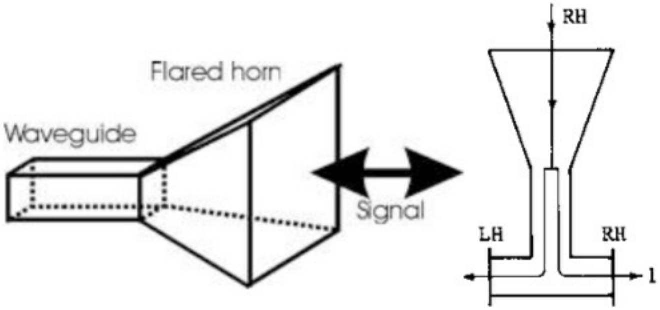
$$P = kTd\nu$$

T is known as the ***antenna temperature***, usually denoted T_A.

For example, a 25-metre telescope, observing a 100 milliJansky (mJy) radio source measures an antenna temperature, T_A, of 0.023K!

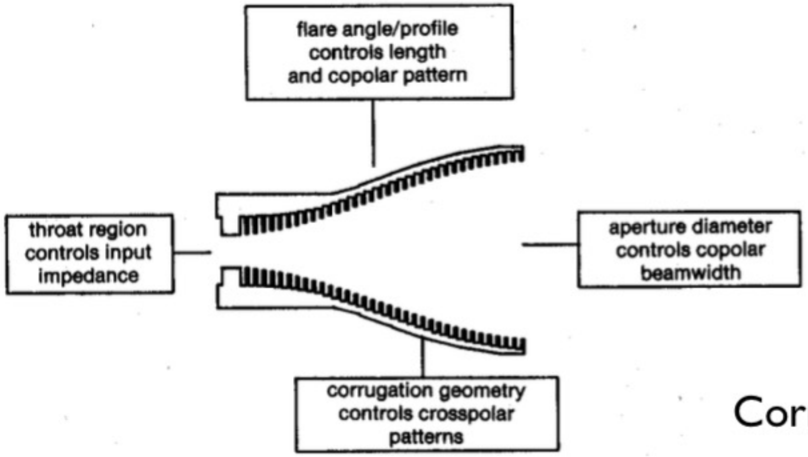
Feedhorns

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 opposite (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.



flare angle/profile controls length and copolar pattern

throat region controls input impedance

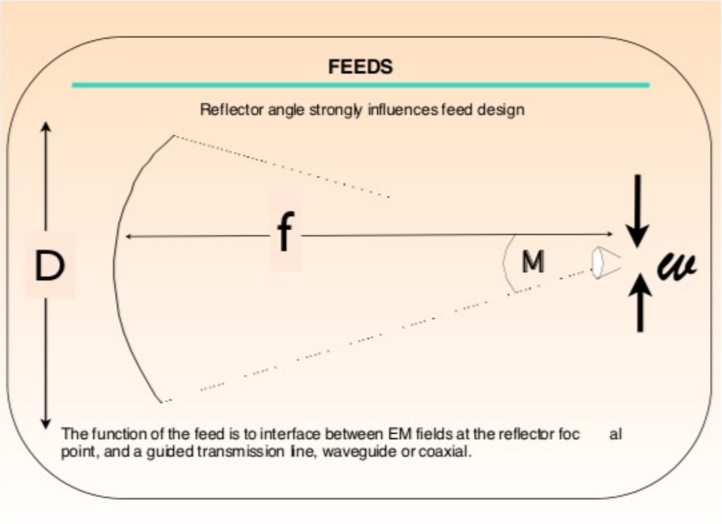
aperture diameter controls copolar beamwidth

corrugation geometry controls crosspolar patterns

Corrugated horns (above) are the most common.

More on Feedhorns

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


FEEDS

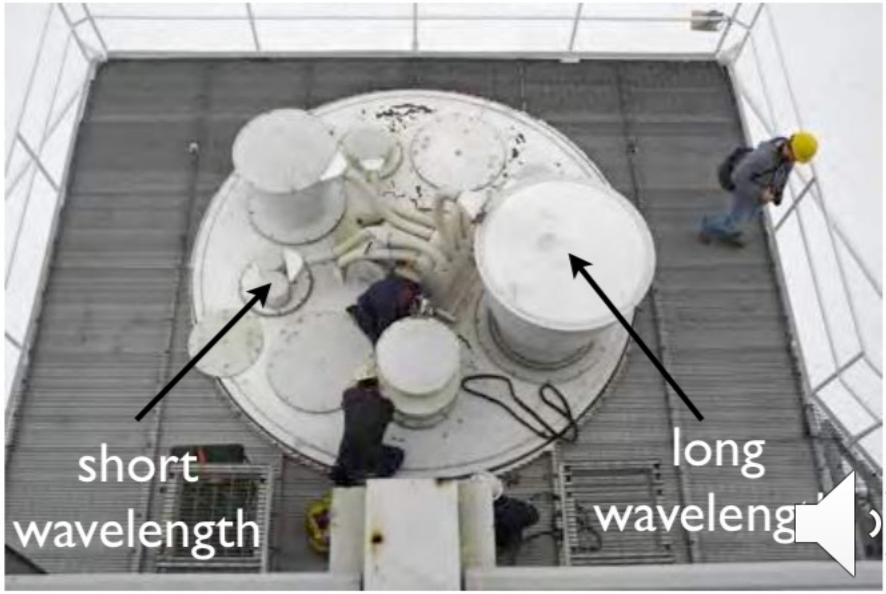
Reflector angle strongly influences feed design

The function of the feed is to interface between EM fields at the reflector focal point, and a guided transmission line, waveguide or coaxial.

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

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

N. B. Feeds become bigger and bigger as we go to longer wavelengths. Right: GBT feeds - the largest is for 21cm.



Illumination

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.

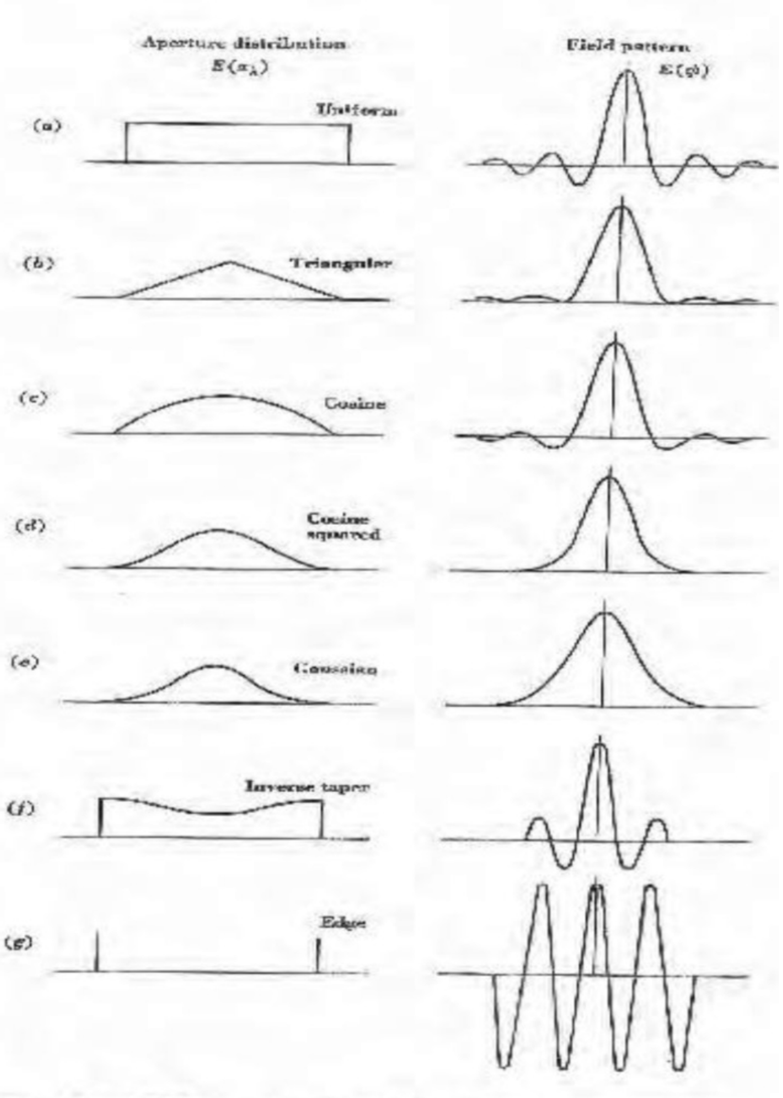


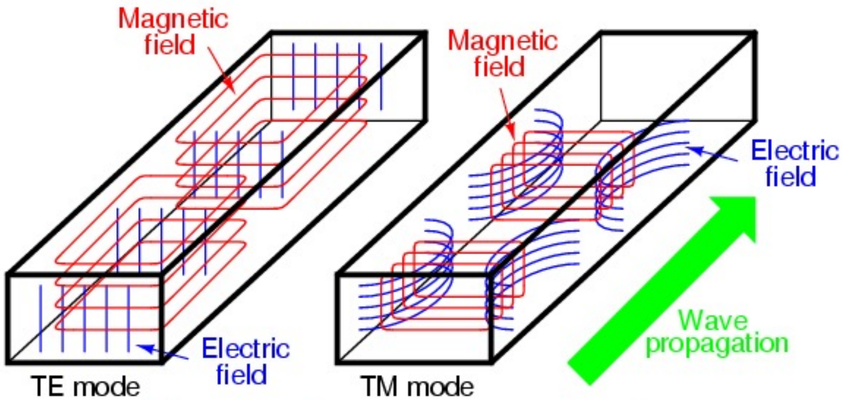
Fig. 6-9. Different aperture distributions with associated antenna patterns

Waveguides

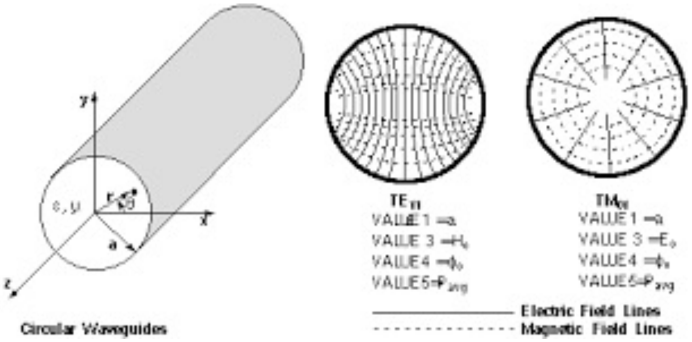
While the feed receives signals focussed by the paraboloid, these signals still need to be fed to a receiver.

This is normally done by means of a ***waveguide***, either square or round in cross section. These structures allow electromagnetic waves to propagate through the waveguide, with minimal loss of signal.

Each guide has a dominant mode, which is the desired mode for optimal propogation. Most commonly used is the TE10 mode in rectangular guides. For circular guides, the TE11 mode is the dominant mode that needs to be excited.



Magnetic flux lines appear as continuous loops
Electric flux lines appear with beginning and end points



Waveguides

To connect a receiver (or transmitter) to a waveguide, we require a waveguide-to-coaxial converter, because most receiver components are designed for coaxial input.

The ideal way to connect to a circular waveguide is to use an ***orthogonal-mode transducer (OMT)***, or alternatively, a ***hybrid polariser***.