Radio Telescope Fundamentals – I

P K Manoharan

Arecibo Observatory
University of Central Florida
(mano@naic.edu)

2021 GBO/AO Single Dish Workshop

Radio Telescope – the Single Dish

- The simplest radio telescope (other than elemental devices such as a dipole or horn) is a parabolic reflector – a ‘single dish’.

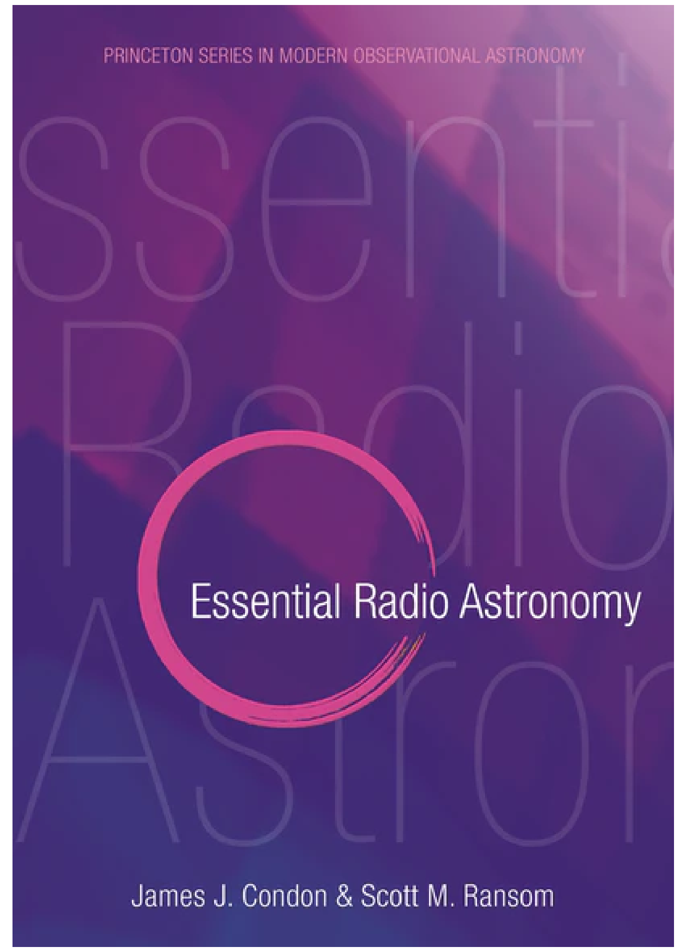
- We discuss characteristics of single dish
  - Reflector
  - Angular response – beam
  - Angular resolution
  - ‘sidelobes’ – finite response at large angles.

Radio Astronomy – Some Reference Books

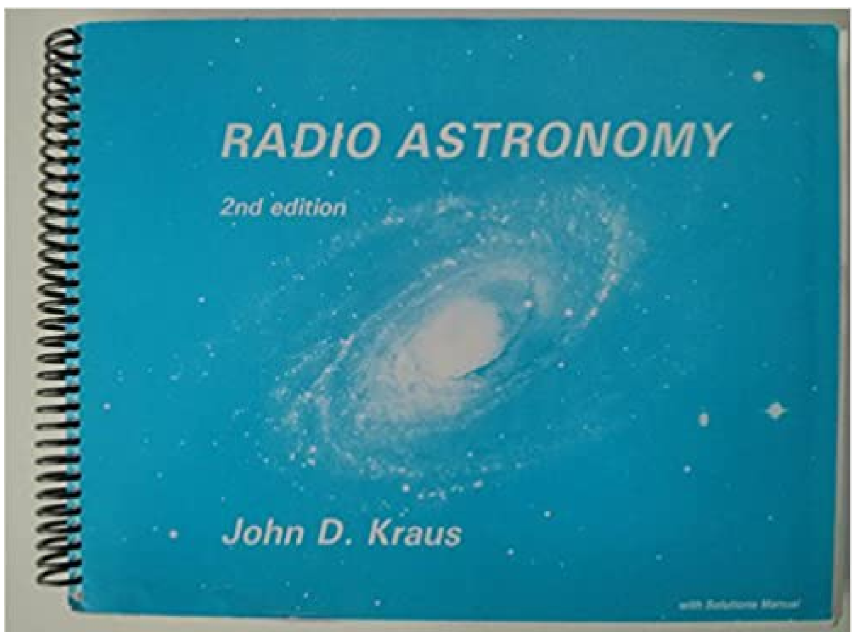
© 2014

Tools of Radio Astronomy

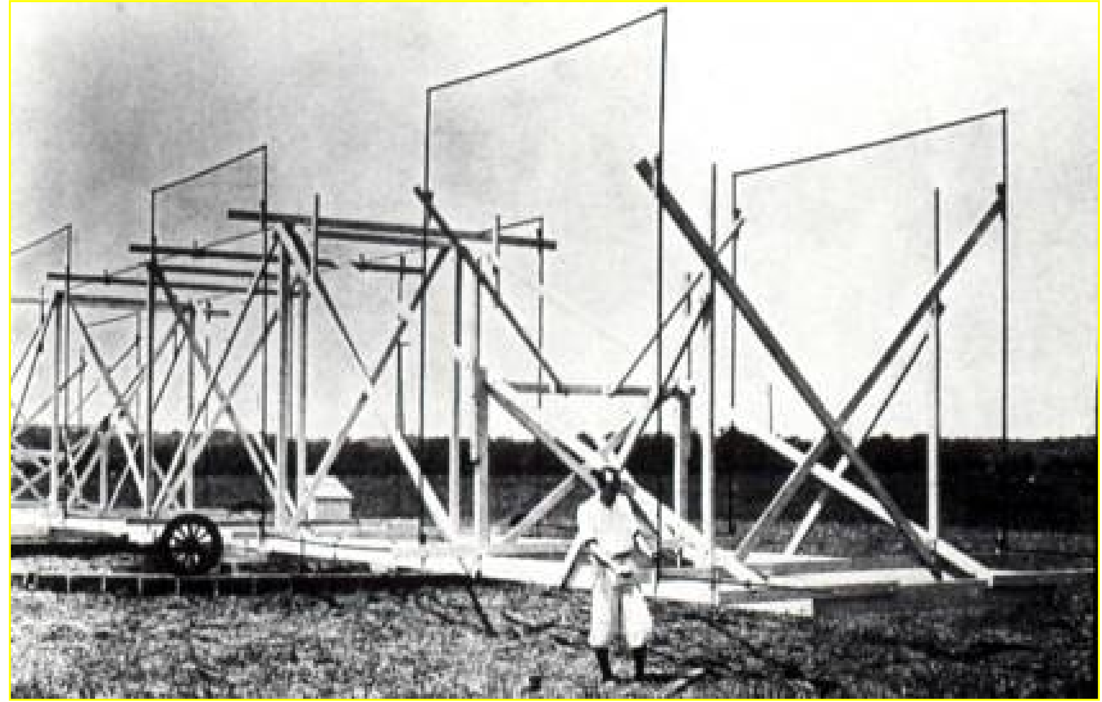
Authors: **Wilson**, Thomas, **Rohlfs**, Kristen, **Huettemeister**, Susanne



Presents the 6th edition of a leading textbook on radio astronomy to include state-of-the-art descriptions of instrumentation and new observations



Karl Jansky

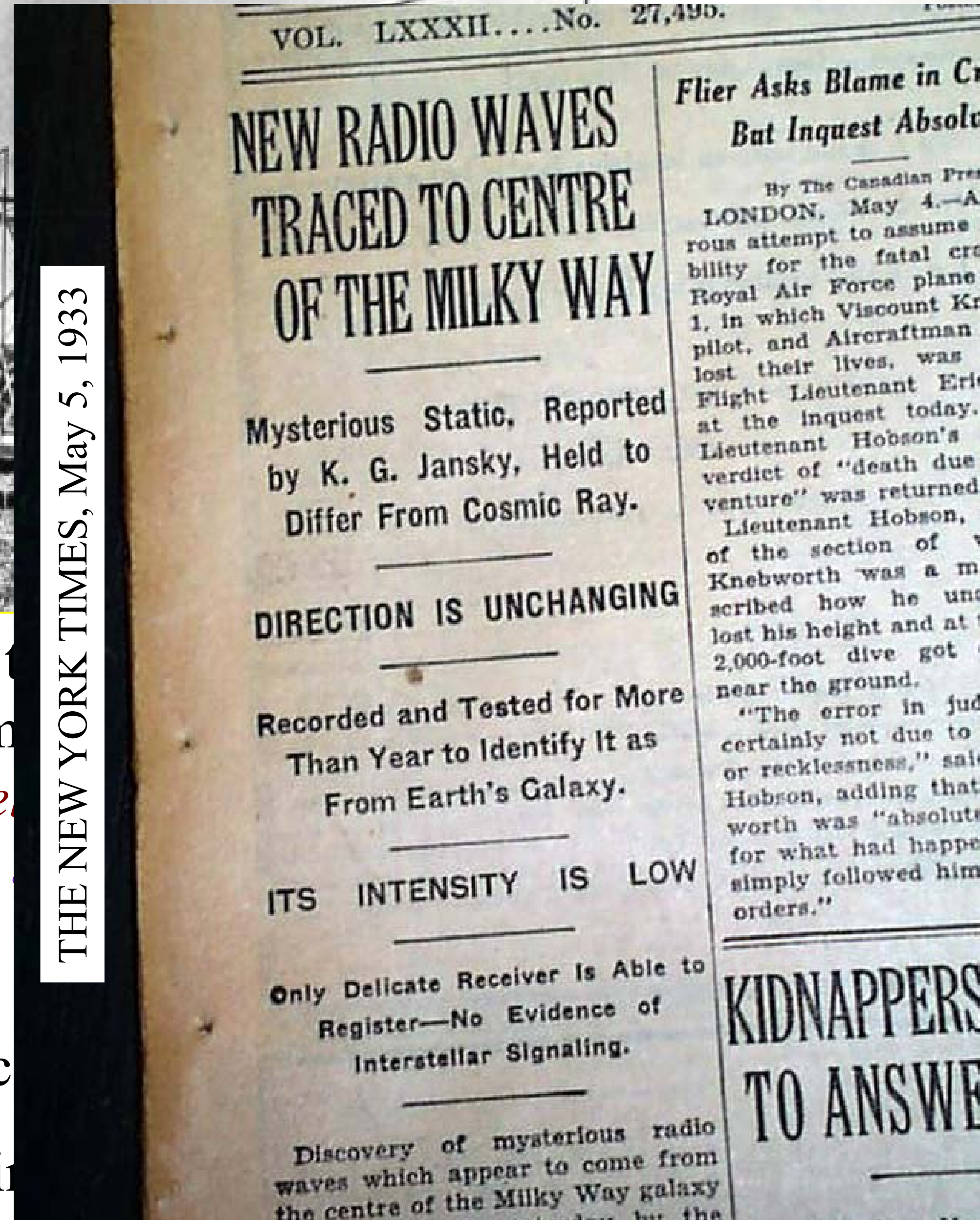


Jansky commissioned an antenna to determine the radio interference and detected radio waves coming from outer space (1932, Bell Telephone Laboratories) *"A new kind of telescope opened a new window!"*

- Bell Labs showed little interest: *"so faint not even interesting as a source of radio interference!"*
- Not accepted by the astronomical community
- Jansky died in 1950 before the importance of his discovery was appreciated

Karl Jansky

THE NEW YORK TIMES, May 5, 1933



VOL. LXXXII....No. 27,495.

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy

Flier Asks Blame in Cra

But Inquest Absolve

By The Canadian Press

LONDON, May 4.—A

rous attempt to assume r

bility for the fatal cras

Royal Air Force plane

1, in which Viscount Kne

pilot, and Aircraftman

lost their lives, was

Flight Lieutenant Eric

at the inquest today.

Lieutenant Hobson's

verdict of "death due

venture" was returned.

Lieutenant Hobson,

of the section of w

Knebworth was a me

scribed how he una

lost his height and at t

2,000-foot dive got d

near the ground.

"The error in judg

certainly not due to

or recklessness," said

Hobson, adding that

worth was "absolute

for what had happen

simply followed him

orders."

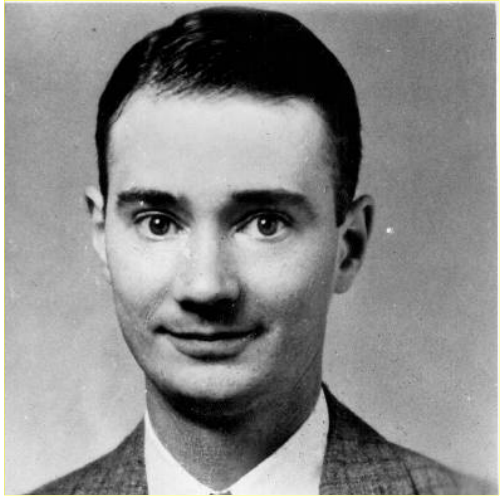
KIDNAPPERS TO ANSWE

Jansky commissioned an antenna t

detected radio waves coming from

Laboratories) *"A new kind of te*

- Bell Labs showed little interest: *of radio interference!"*
- Not accepted by the astronomic
- Jansky died in 1950 before the i appreciated



Discovery of the non-thermal Universe

Grote Reber continued and detected cosmic radiation by going to **longer** wavelengths (1939)

- ✗ 3300 MHz
- ✗ 900 MHz
- ✔ 160 MHz

- Radiation had to be non-thermal
  - No theoretical basis at the time
  - 1949 *Anomalous* solar emission
  - 1950 Synchrotron radiation theory
    - ~10 years after Reber

Reber's ~9.6 m parabolic radio telescope (originally constructed in Wheaton, Illinois, NSF/AUI)

Radio Telescopes

- Similar to optical reflecting telescopes
- Due to long wavelength, less sensitive to surface imperfections
- Large reflecting surfaces (e.g., single dish)
- A single dish can have a good potential sensitivity

Introduction to Radio Telescopes

Terms and Concepts

Parabolic reflector
Blocked/unblocked
Subreflector
Frontend/backend
Feed horn
Local oscillator
Mixer
Noise Cal
Flux density

Introduction to Radio Telescopes

Terms and Concepts

Parabolic reflector
Blocked/unblocked
Subreflector
Frontend/backend
Feed horn
Local oscillator
Mixer
Noise Cal
Flux density

Jansky
Bandwidth
Resolution
Antenna power pattern
Half-power beamwidth
Side lobes
Beam solid angle
Main beam efficiency
Effective aperture

Introduction to Radio Telescopes

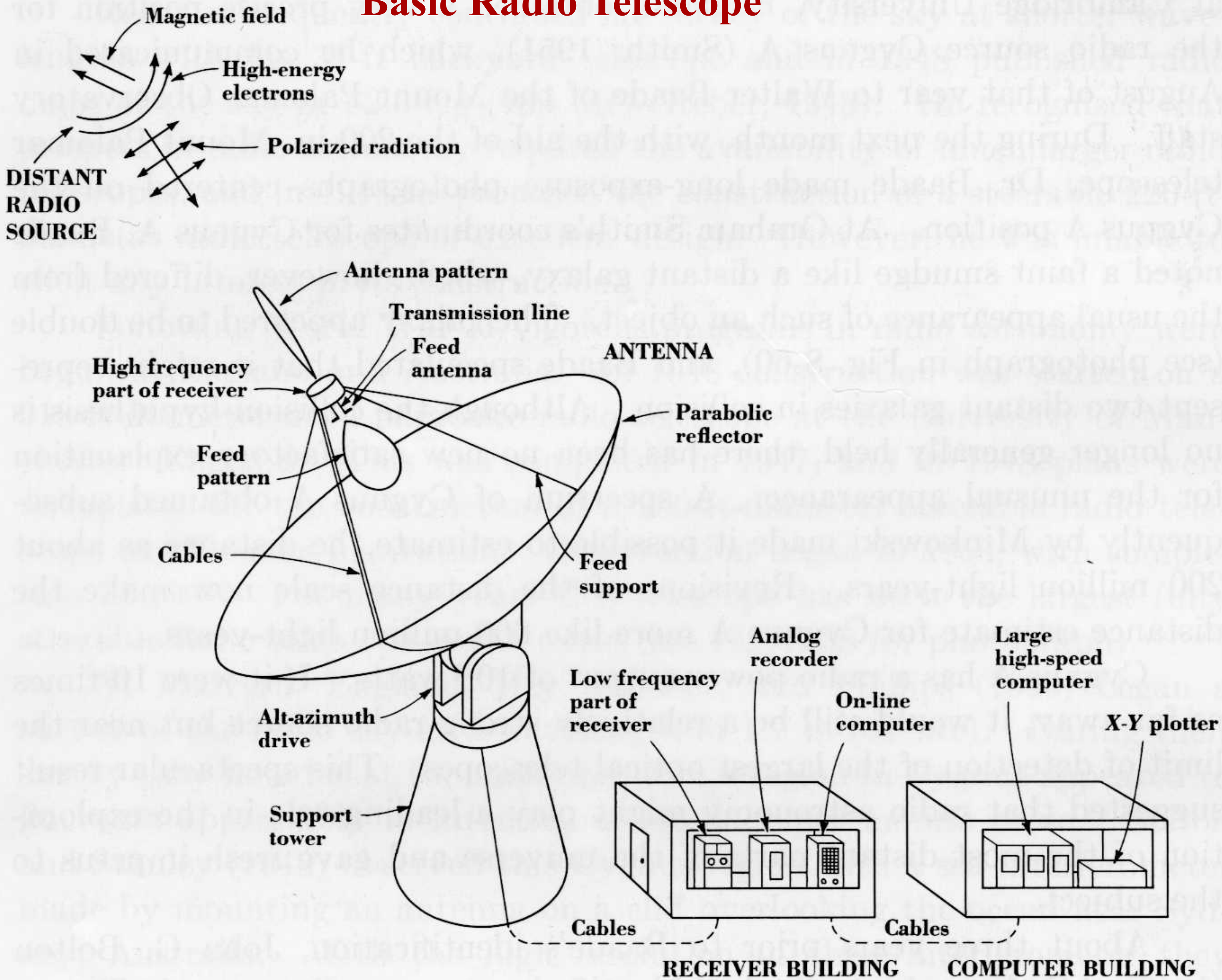
Terms and Concepts

Parabolic reflector
Blocked/unblocked
Subreflector
Frontend/backend
Feed horn
Local oscillator
Mixer
Noise Cal
Flux density

Jansky
Bandwidth
Resolution
Antenna power pattern
Half-power beamwidth
Side lobes
Beam solid angle
Main beam efficiency
Effective aperture

Aperture efficiency
Antenna Temperature
Aperture illumination function
Spillover
Gain
System temperature
Receiver temperature
convolution

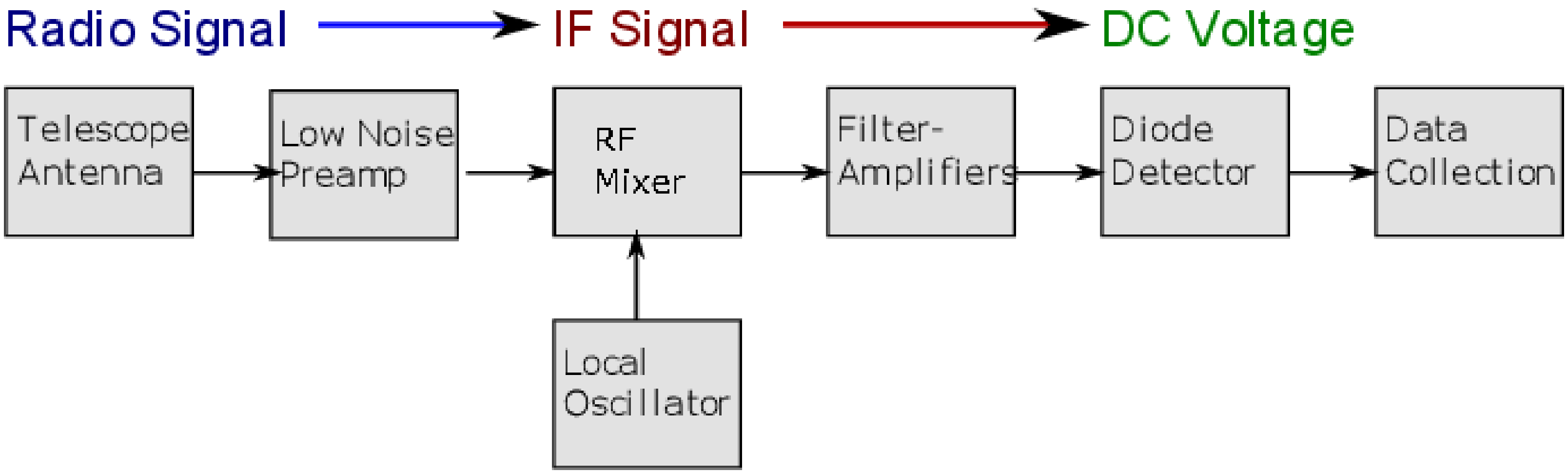
Basic Radio Telescope



Kraus, 1966. Fig.1-6, p. 14.

Fig. 1-6. A modern radio telescope.

Components of a radio telescope

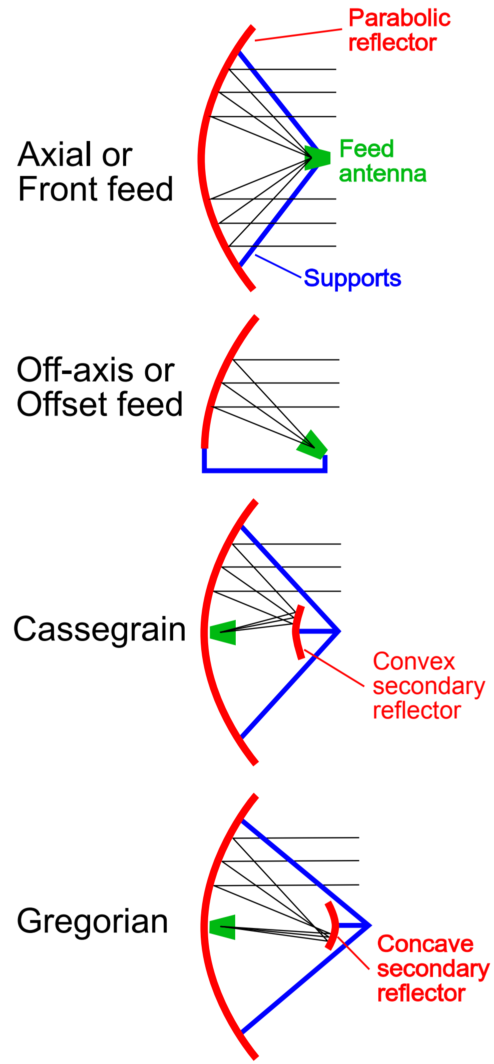


Typical Radio Telescope Antennas

- Parabolic: The primary mirror is a parabola
- Steerable: The antenna can move in 2 angular directions to track a source across the sky.
- Alt-Az Mount: The antenna tracks in altitude (elevation) and azimuth
- Cassegrain focus: A secondary mirror (subreflector) is placed in front of the prime focus of the primary reflector and focuses the radio waves to a receiver located behind the main reflector.
- On-axis: The antenna axis is the same as the optical axis, resulting in a symmetric antenna.

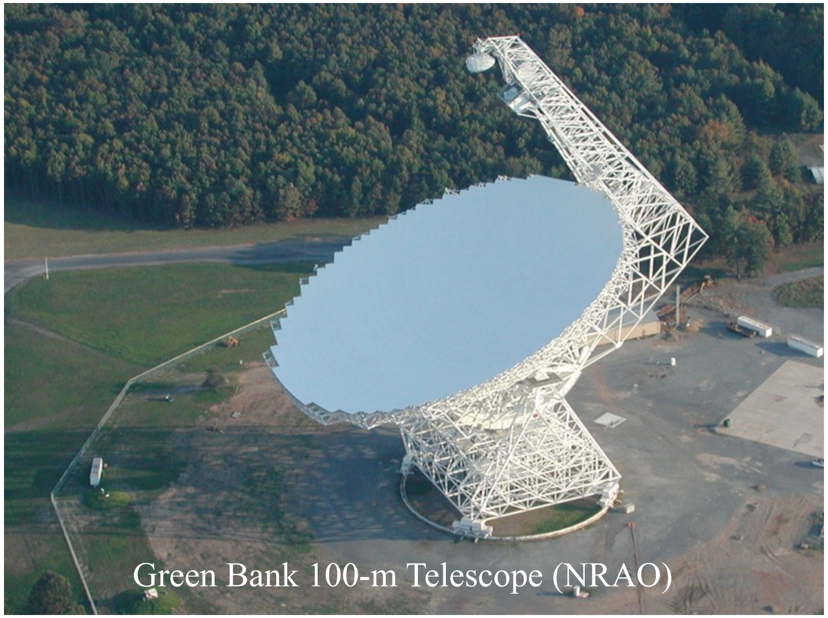
Optical Design of Radio Telescopes

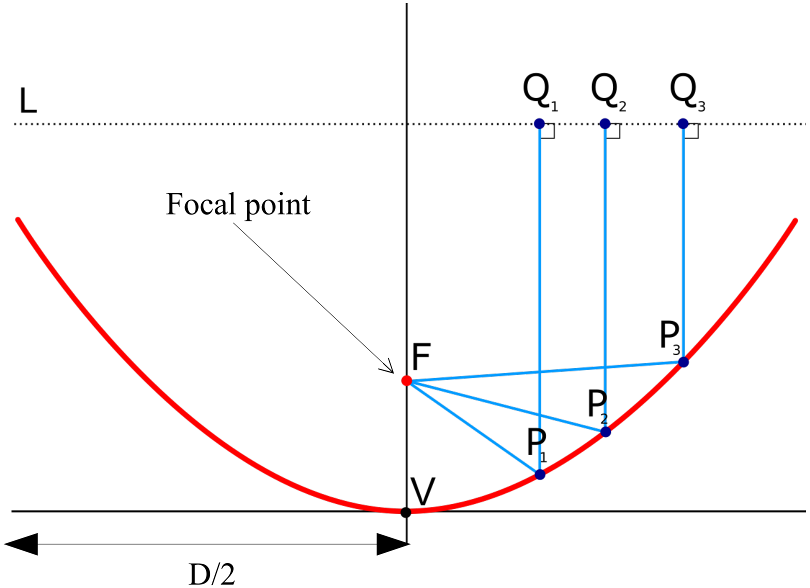
- Prime focus
- Off-axis (or offset feed)
- Cassegrain
- Gregorian

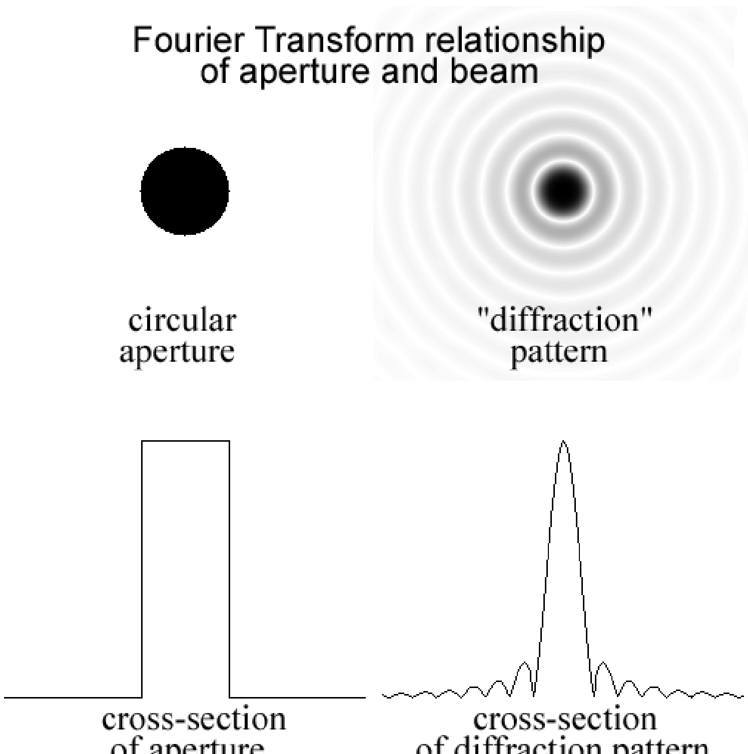


https://en.wikipedia.org/wiki/Cassegrain_antenna

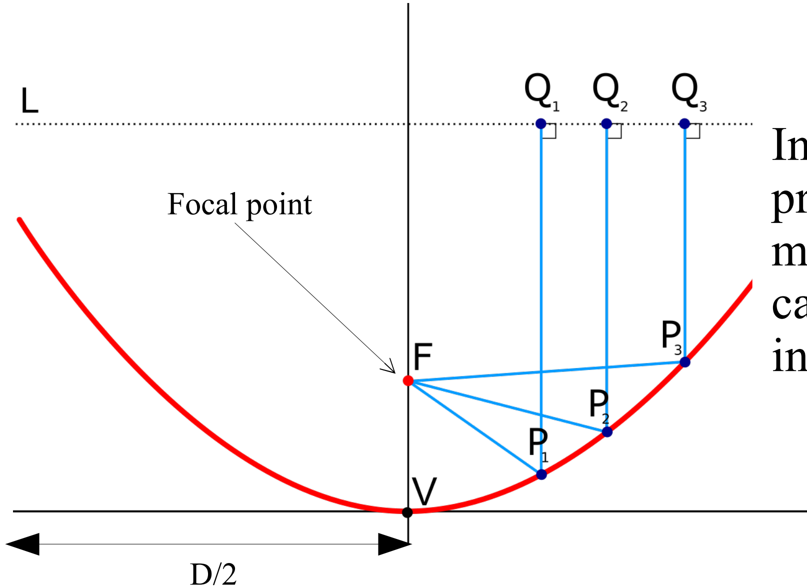
Examples of radio telescope



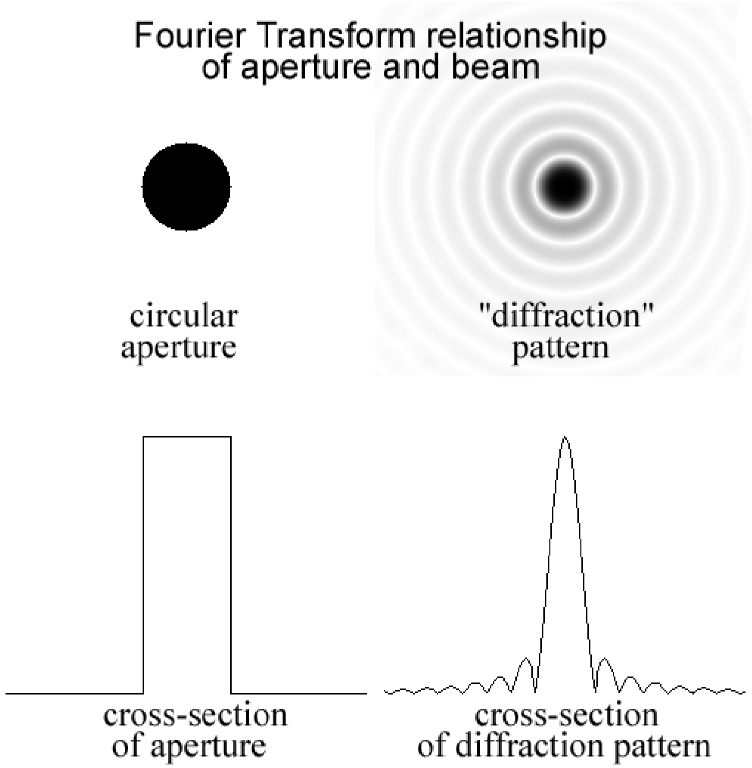




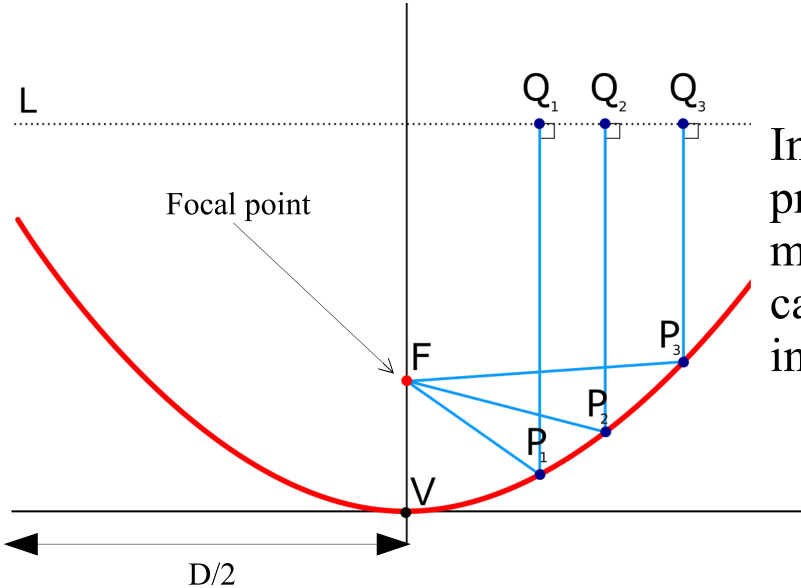
https://web.njit.edu/~gary/728/Lecture4.html



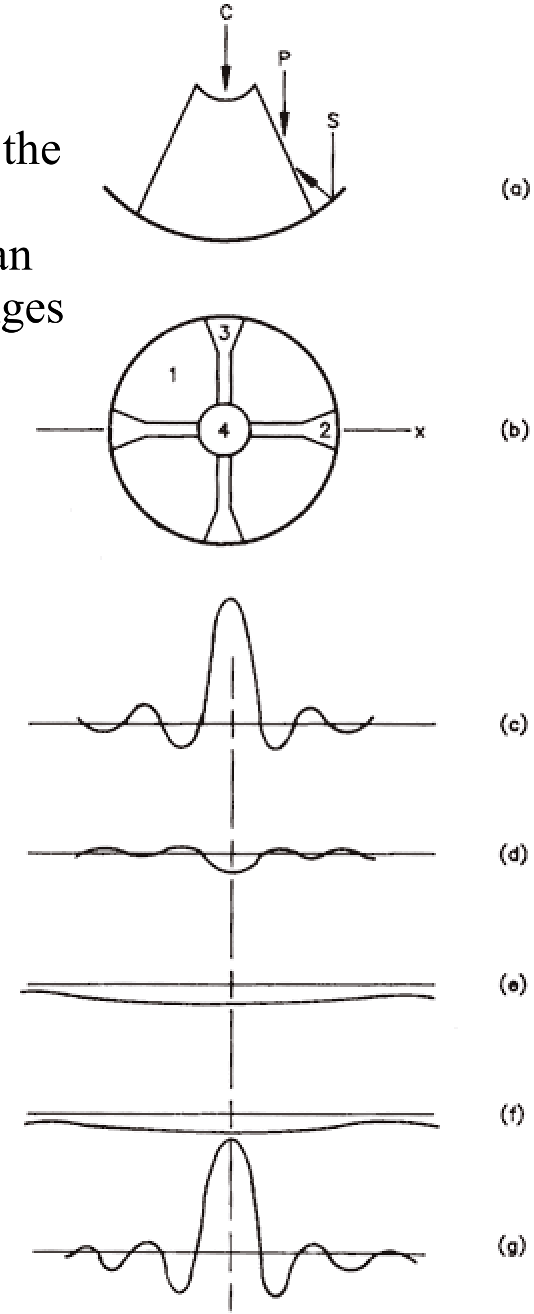
In a reflecting telescope, the presence of a secondary mirror and its supports can causes considerable changes in the diffraction pattern

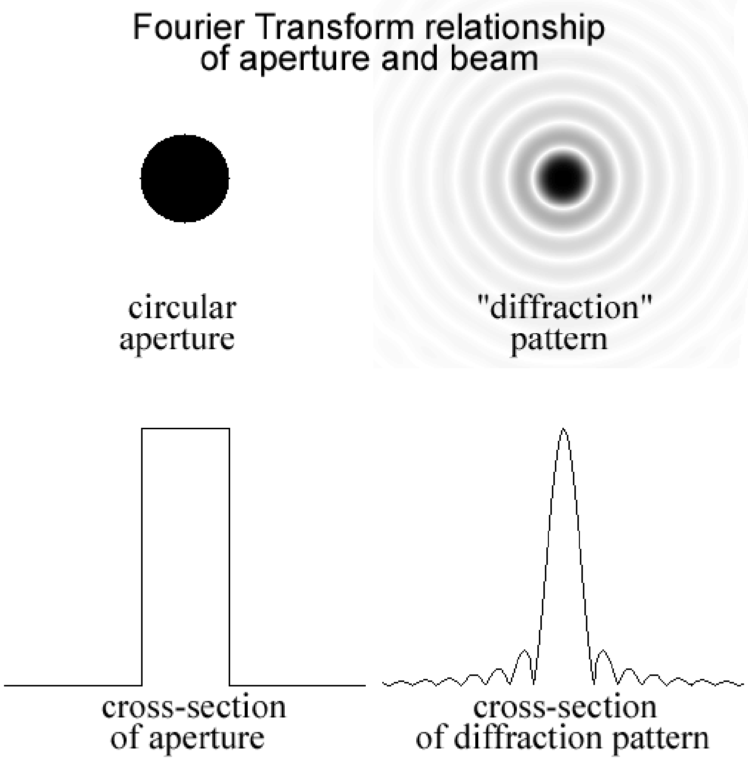


https://web.njit.edu/~gary/728/Lecture4.html

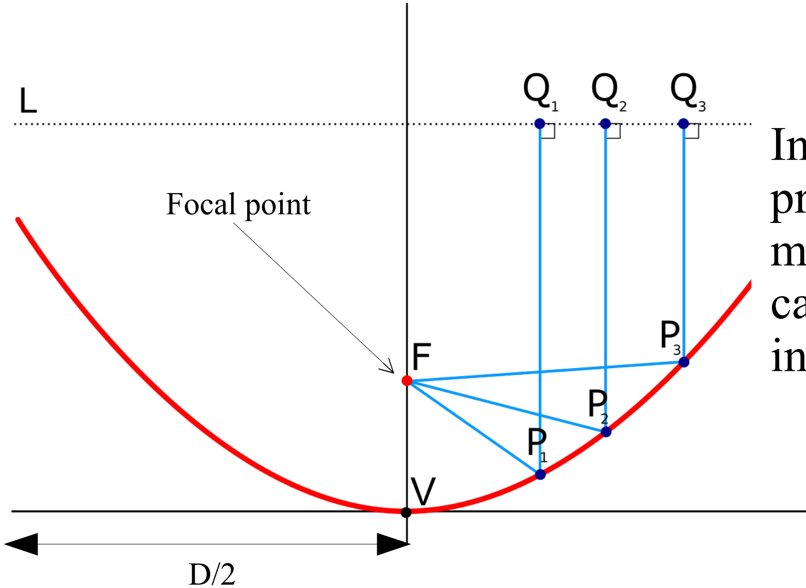


In a reflecting telescope, the presence of a secondary mirror and its supports can causes considerable changes in the diffraction pattern

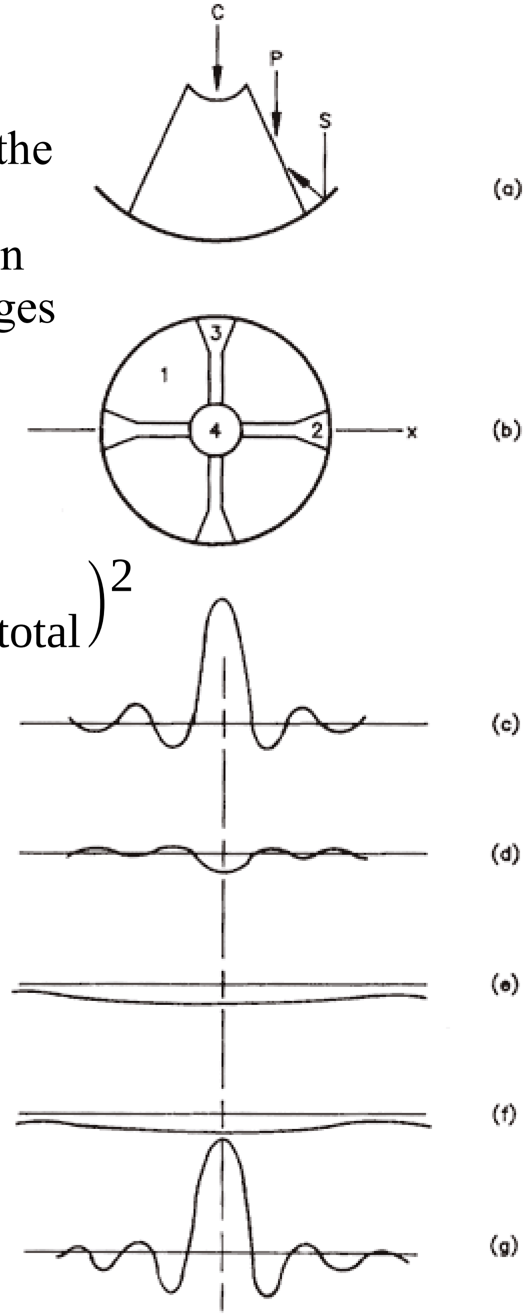




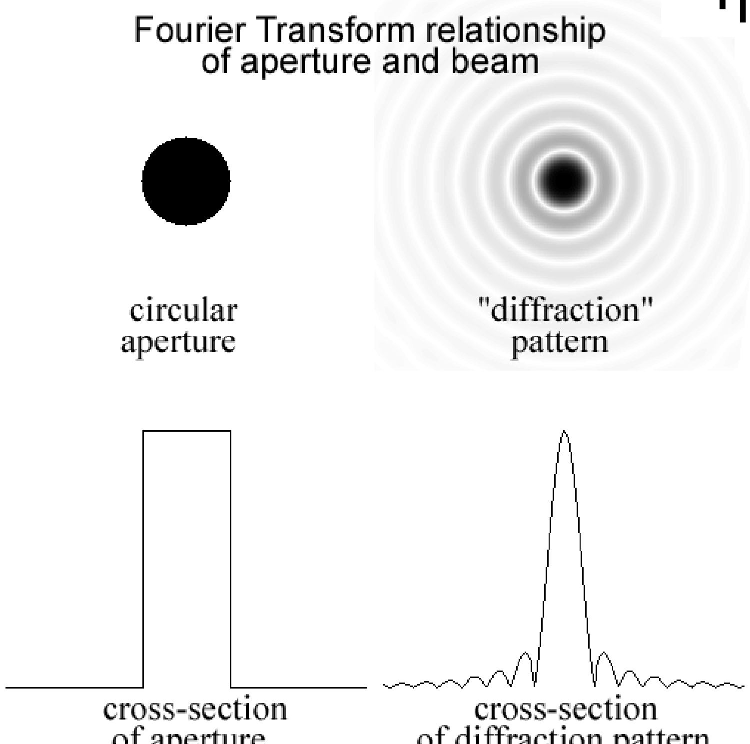
https://web.njit.edu/~gary/728/Lecture4.html



In a reflecting telescope, the presence of a secondary mirror and its supports can causes considerable changes in the diffraction pattern



$$\eta = \left(1 - A_{\text{block}} / A_{\text{total}}\right)^2$$

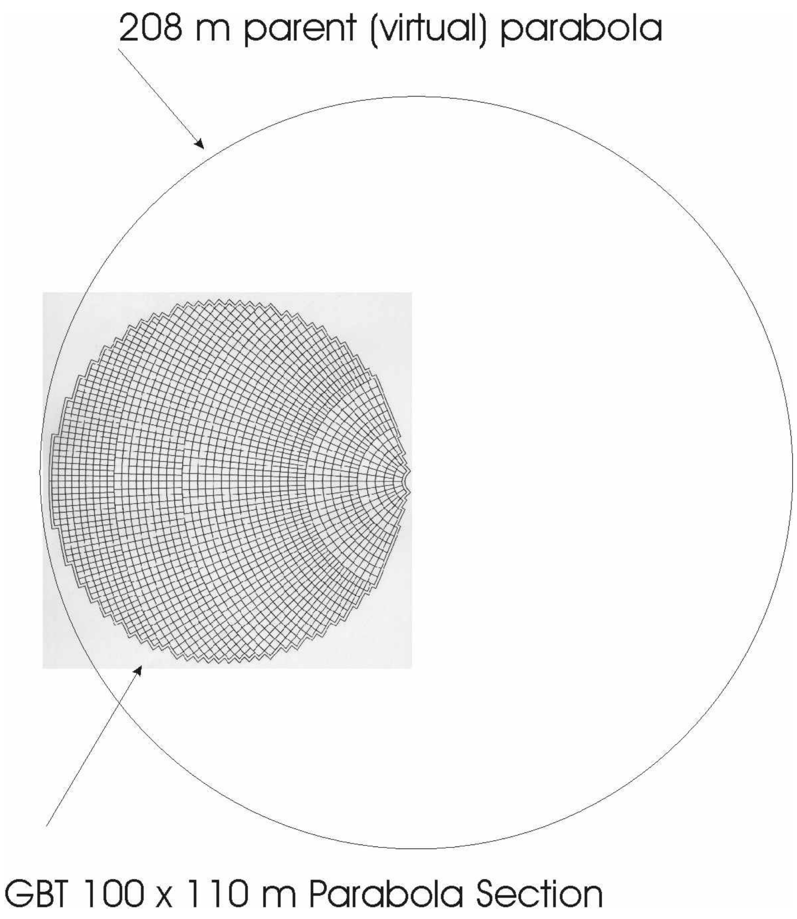


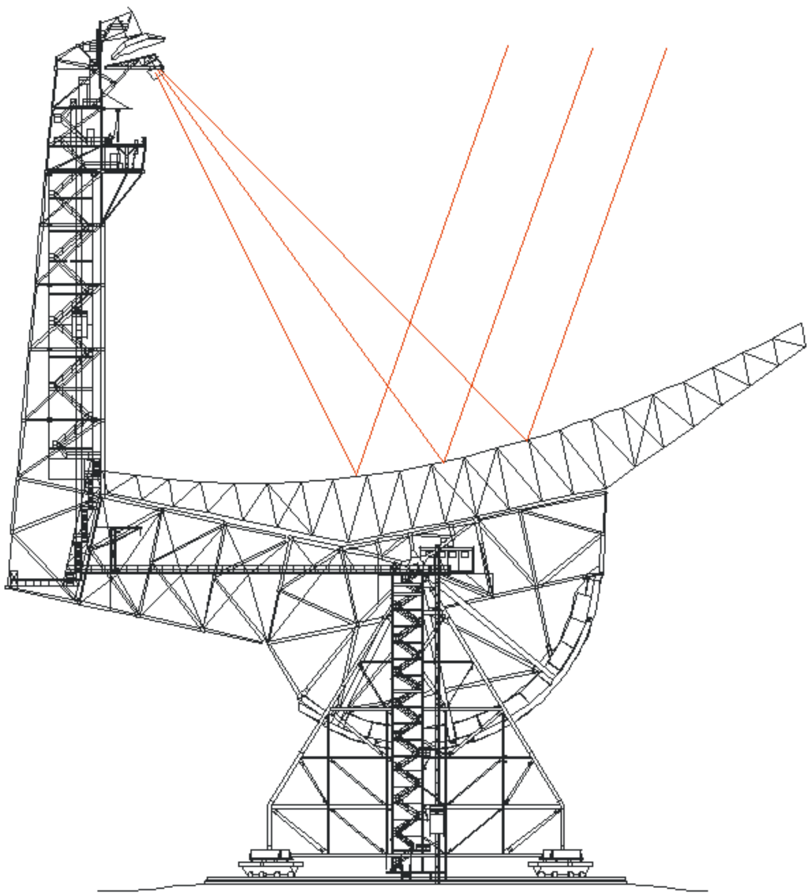
https://web.njit.edu/~gary/728/Lecture4.html

Unblocked Aperture – GBT

100 x 110 m section of a parent parabola 208 m in diameter

Cantilevered feed arm is at focus of the parent parabola

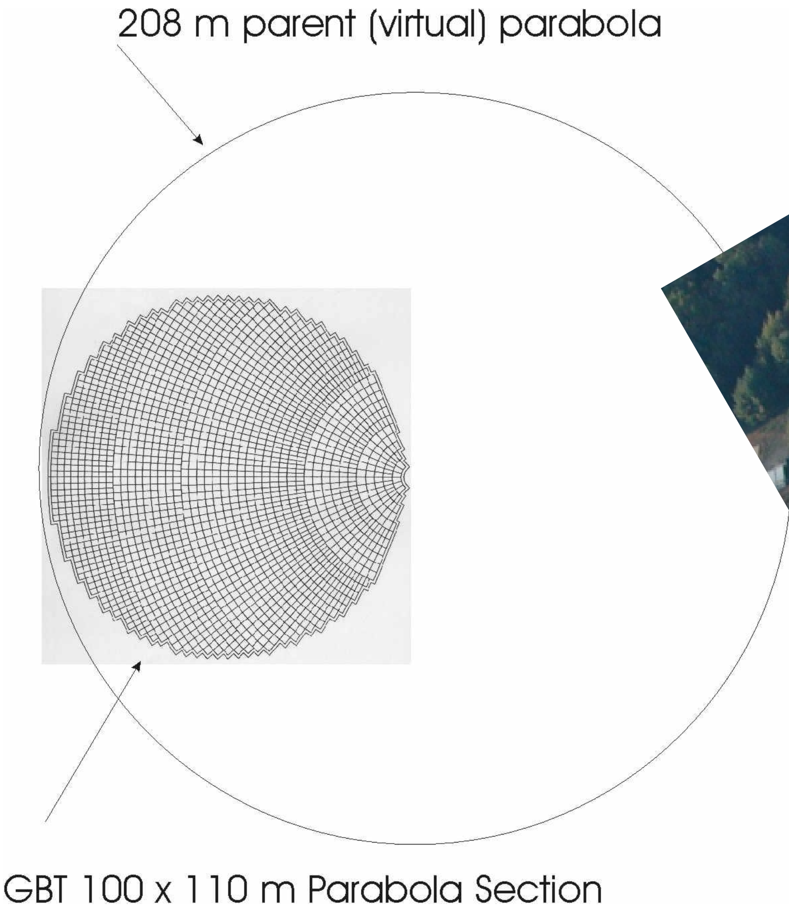


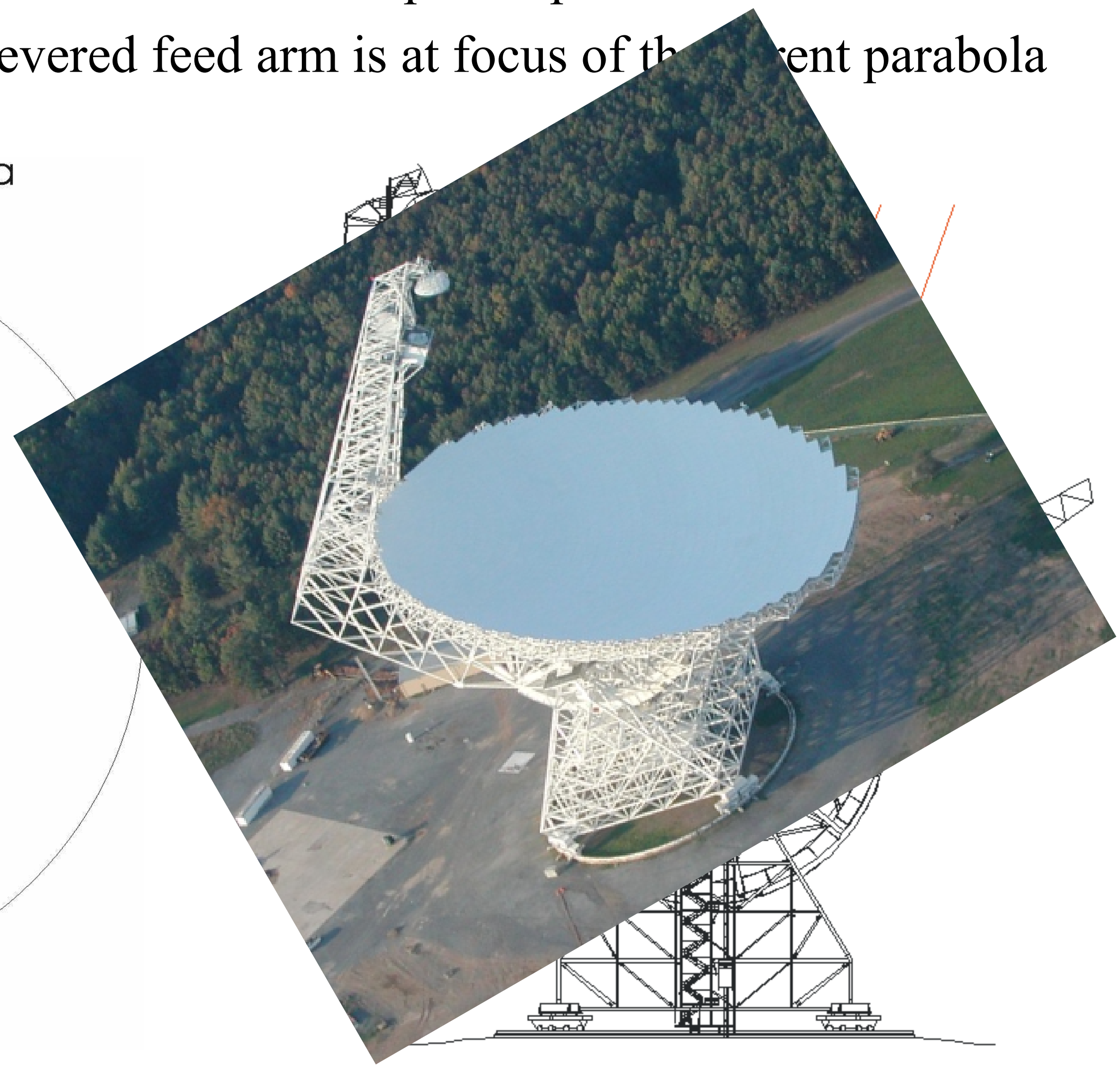


Unblocked Aperture – GBT

100 x 110 m section of a parent parabola 208 m in diameter

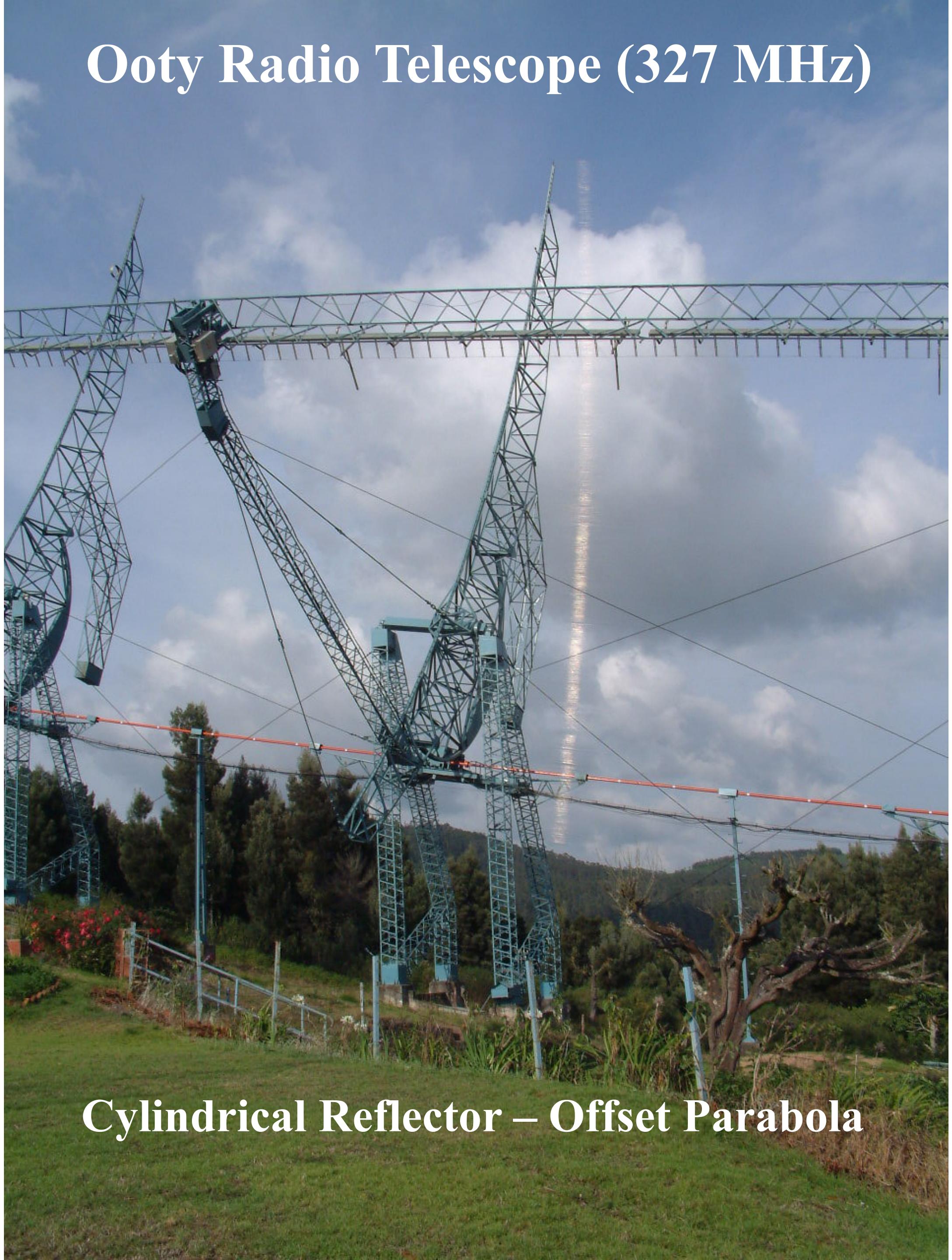
Cantilevered feed arm is at focus of th ent parabola



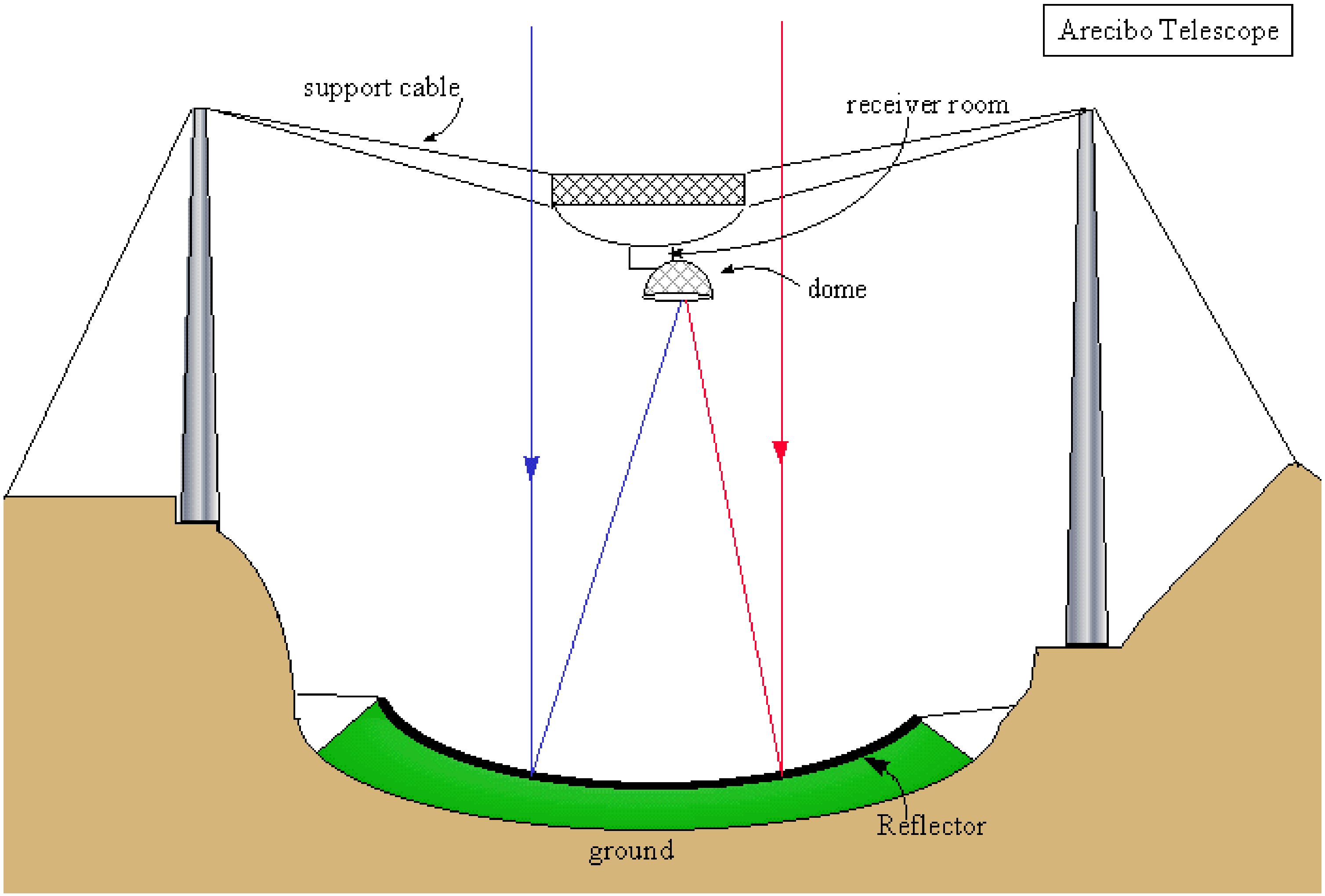


GBT Main Features

- Telescope diameter: 100 m
- Fully steerable antenna
  - Elevation Limits: Lower limit: 5 degrees; Upper limit: ~ 90 degrees; 85% coverage of the celestial sphere.
- Unblocked aperture
  - Optics: 110 m x 100 m unblocked section of a 208 m parent paraboloid; offaxis feed arm
- Active surface
  - Allows for compensation for gravitational and thermal distortions.
- Frequency coverage of 0.1 to 120 GHz (3m – 2.6mm)
- Location in the National Radio Quiet Zone


Ooty Radio Telescope (327 MHz)
Cylindrical Reflector – Offset Parabola

Arecibo Telescope

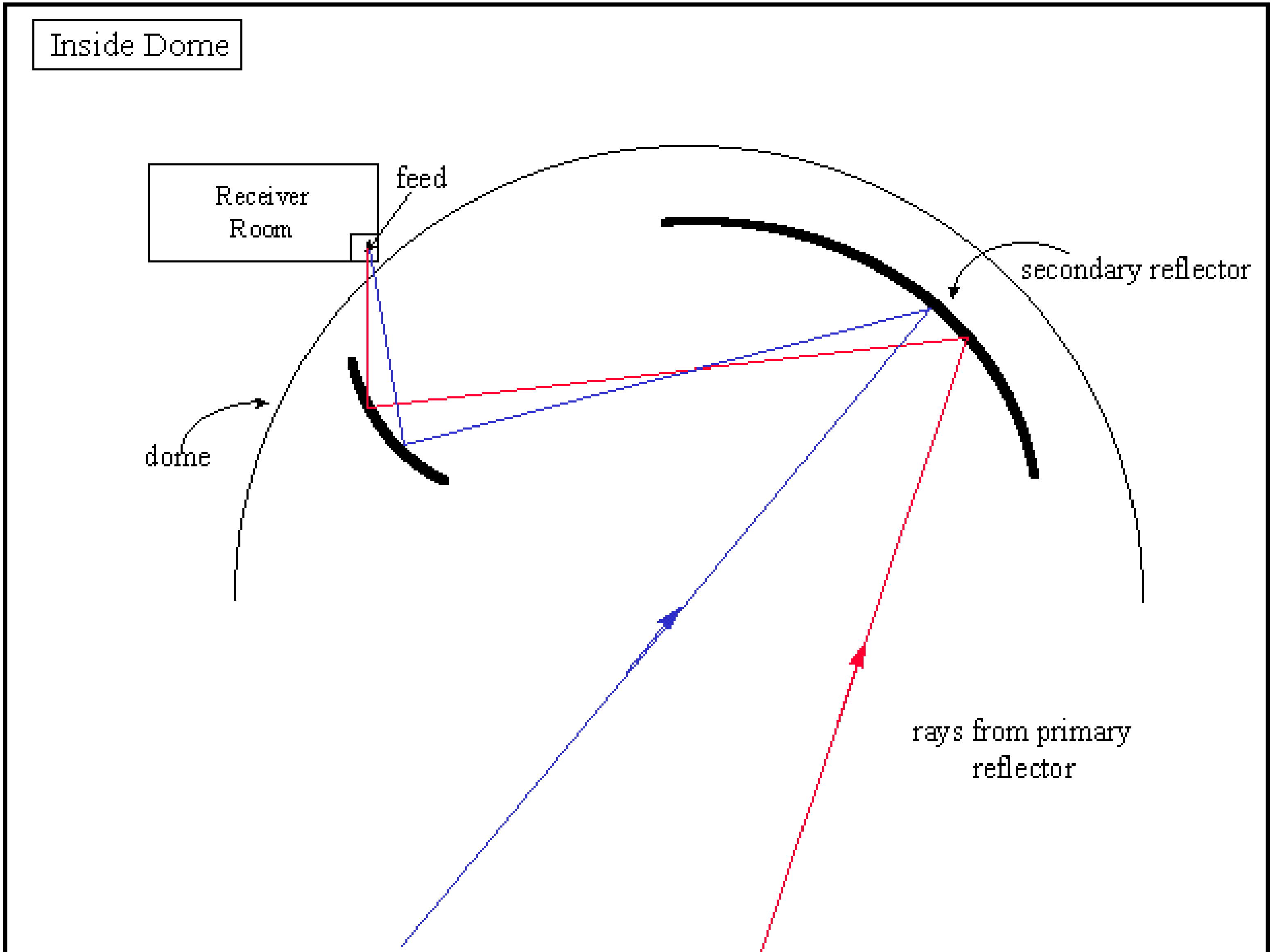


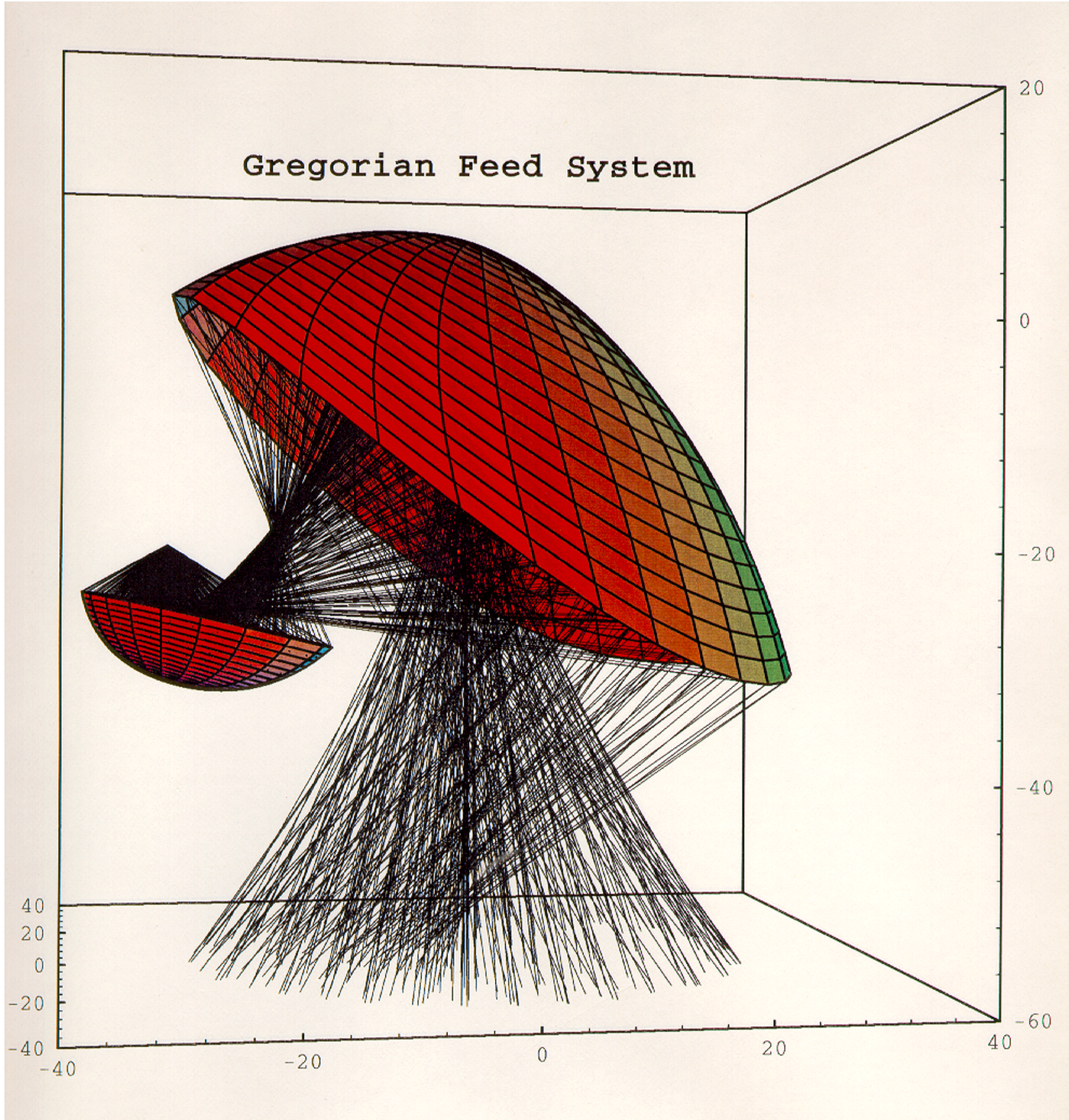
Fixed spherical reflector of size 305 m

Gregorian

- The dome is referred to as the "Gregorian".

- Gregorian – the secondary reflector is placed behind the focal point of the primary reflector.
- Advantages
  - Gregorian dome protects the receivers from RFI and weather
  - For example, a line feed can cover only a narrow frequency band and a limited number of line feeds can be used at one time
  - With Gregorian optics, an array of receivers covering the whole 1-10 GHz range can be easily moved onto the single focal point where the incoming signal is focused.


Inside Dome
Receiver
Room
feed
secondary reflector
dome
rays from primary
reflector



Gregorian Feed System
20
0
-20
-40
-60
40
20
0
-20
-40
-40
-20
0
20
40

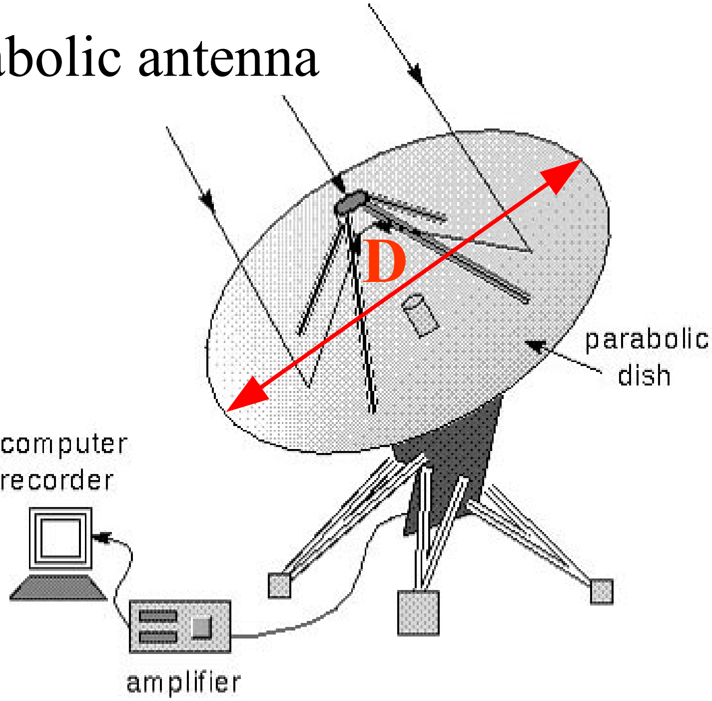
Radio Telescope – Resolution

Resolution of a single dish antenna of diameter **D**,

$$\Theta \sim 1.22\ \lambda/D$$

(i.e., width of the field of view or beam of the antenna)

Parabolic antenna



Unresolved (point) Source: $\Theta_{source} < \Theta$

The telescope measures the brightness integrated over the entire source (i.e., total flux density of the source).

Extended Source: $\Theta_{source} > \Theta$

The telescope pointing will measure only the flux from the source within the beam and the integral is to be taken over the beam size.

Beams of most radio telescopes are nearly Gaussian, and their beamwidths are usually specified by the angle θ_{HPBW} between the half-power points.

Radio Telescope – Resolution

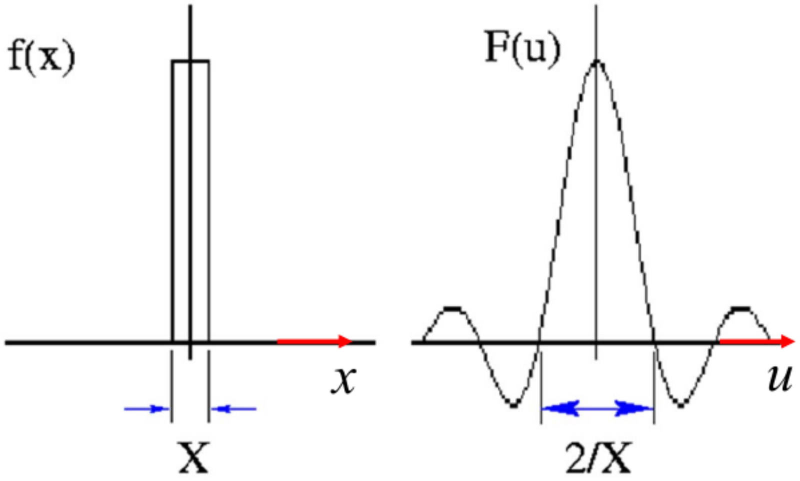
Resolution of a single dish antenna of diameter **D**,

$$\Theta \sim 1.22\ \lambda/D$$

(i.e., width of the field of view or beam of the antenna)

Unresolved (point) Source: $\Theta_{source} < \Theta$

The telescope measures the brightness integrated over the entire source (i.e., total flux density of the source).



Extended Source: $\Theta_{source} > \Theta$

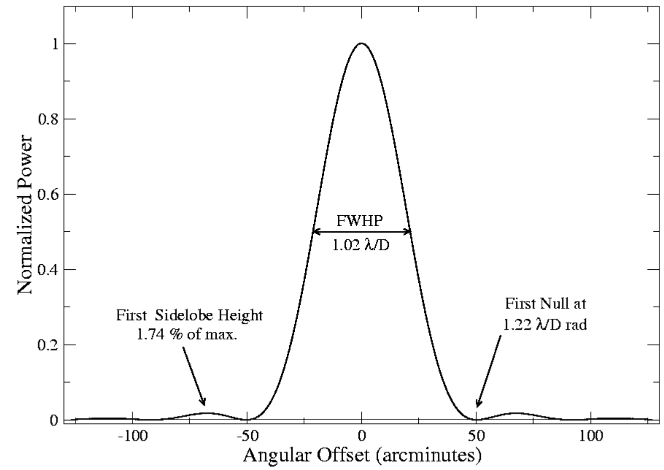
The telescope pointing will measure only the flux from the source within the beam and the integral is to be taken over the beam size.

Beams of most radio telescopes are nearly Gaussian, and their beamwidths are usually specified by the angle θ_{HPBW} between the half-power points.

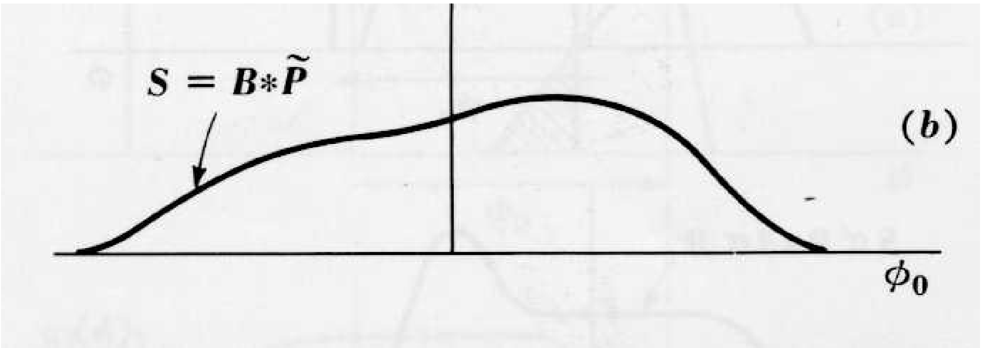
Convolution with the Beam and Smoothing by the beam

Beams of most radio telescopes are nearly Gaussian, and their beamwidths are usually specified by the angle Θ_{FWHM}

The scan across a point source will yield exactly the beam pattern.

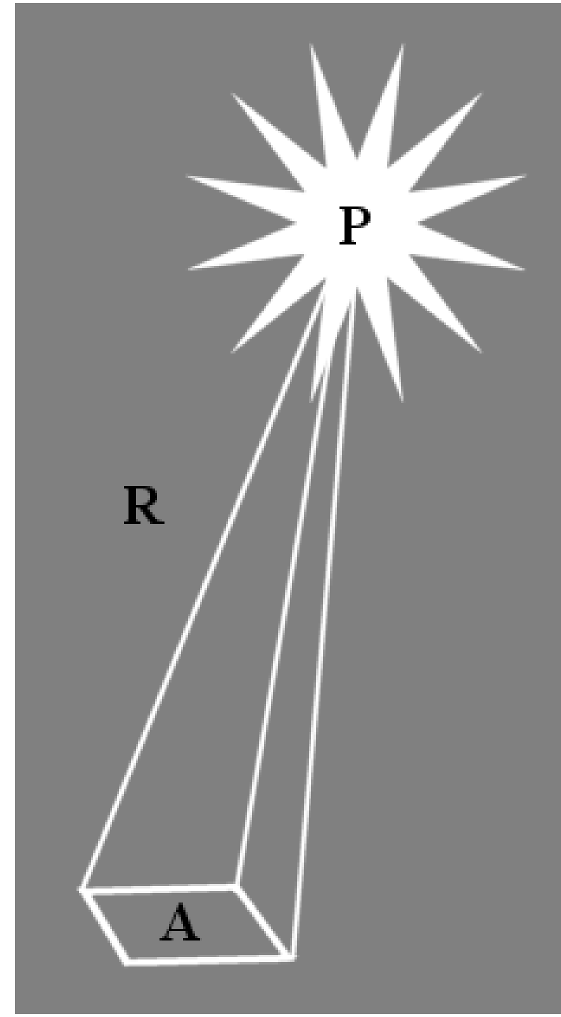


When the source is extended, the true brightness distribution is convolved with the beam pattern.



Smoothing: The antenna pattern is not sensitive to small scale structures present within the source.

Antenna power and Gain



Power collected by an antenna is

$\mathbf{P = S \times A \times \beta}$ (flux density = power/area/bandwidth)

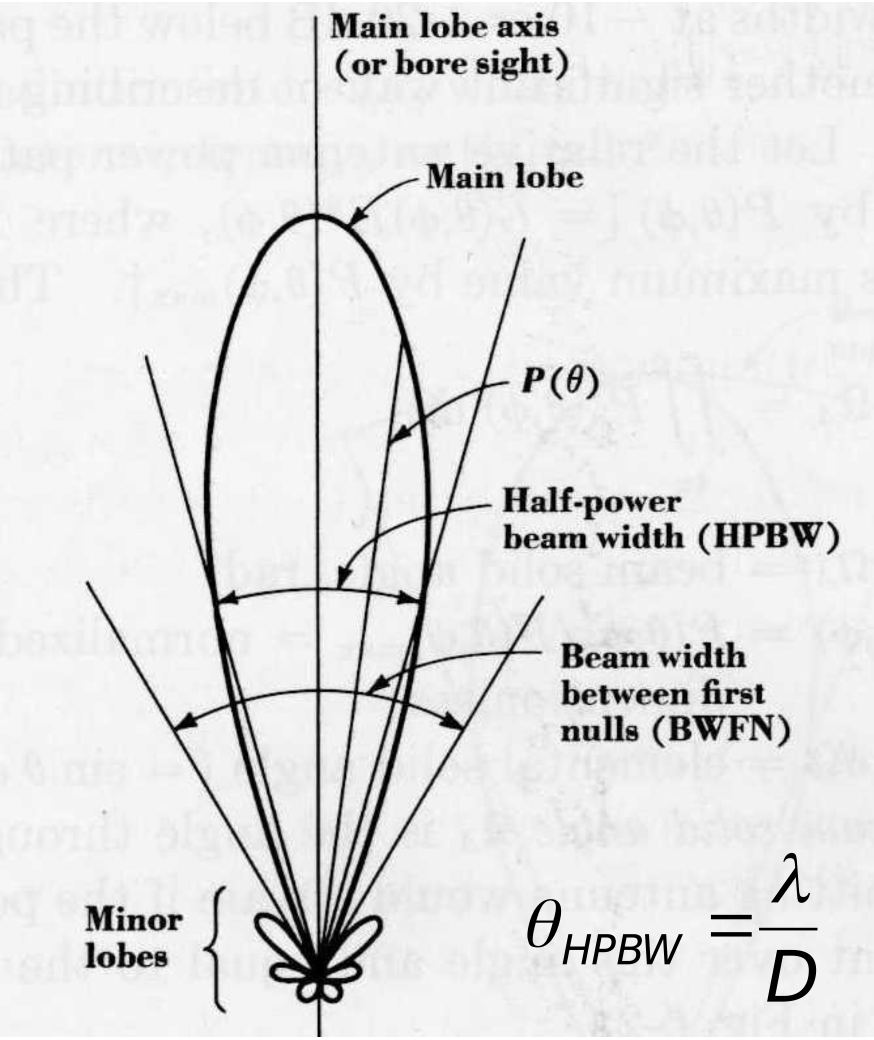
S = flux at Earth, A = antenna area,
β = bandwidth of measured radiation

Gain of an antenna is $\mathbf{G = 4\pi A/\lambda^2}$

Aperture efficiency is the ratio of the effective collecting area to the actual collecting area! ($\eta_{aperture} = A_{eff}/A$)

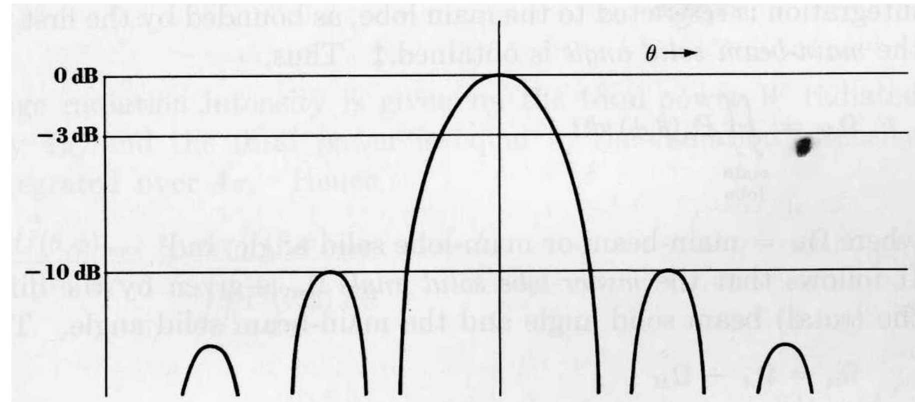
"Jansky" is the unit of flux density (S), $1\text{ Jy} = 10^{-26}\, Watts\,/\,m^2\,/\,Hz$

Antenna Beam Pattern (power pattern)



$$\theta_{HPBW} = \frac{\lambda}{D}$$

Kraus, 1966. Fig.6-1, p. 153.



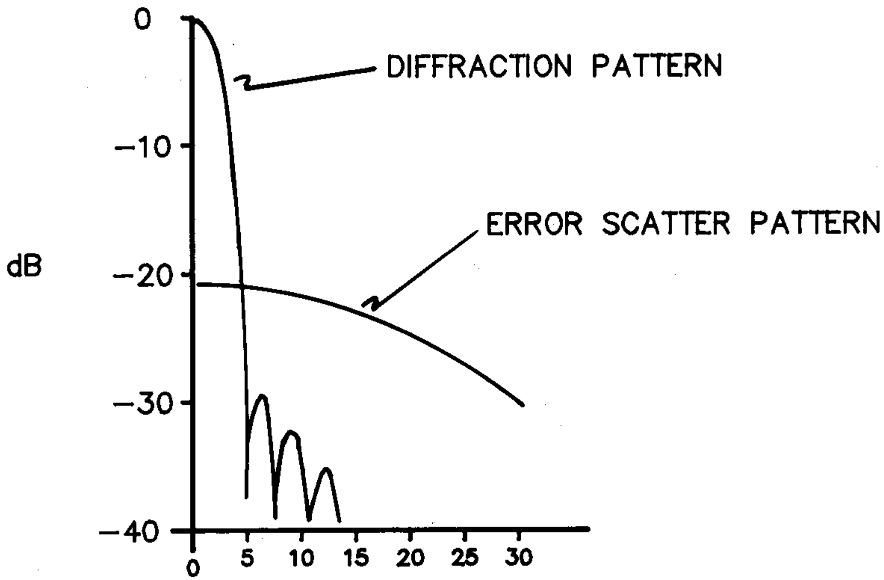
Beam Solid Angle (steradians) $$\Omega_A = \iint_{4\pi} P_n(\theta,\phi)\, d\Omega$$

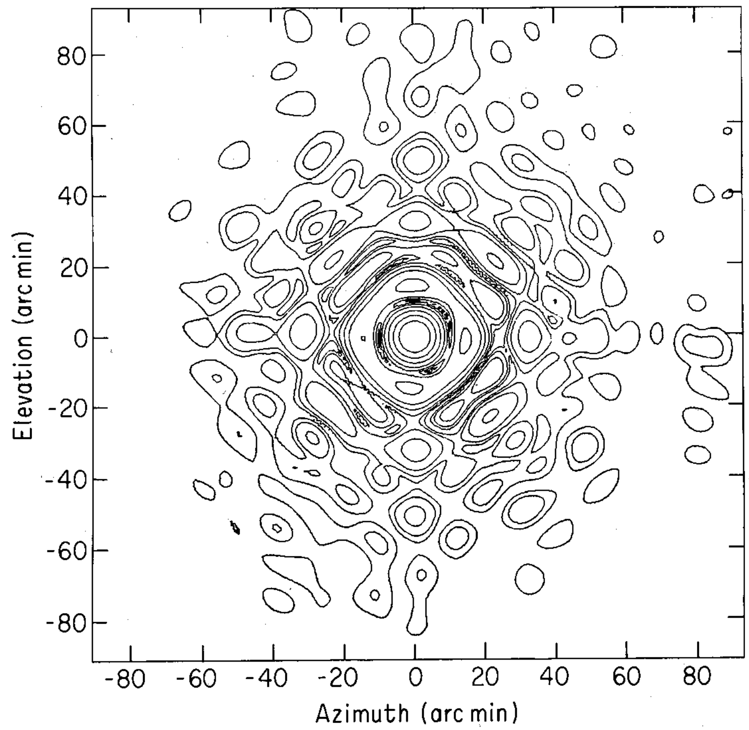
Main Beam Solid Angle $$\Omega_M = \iint_{\substack{main\\lobe}} P_n(\theta,\phi)\, d\Omega$$

(P_n = normalized power pattern)

$$\eta_{main\,beam} = \frac{\Omega_M}{\Omega_A} \qquad \lambda^2 = A_e\,\Omega_M$$

Primary Beam



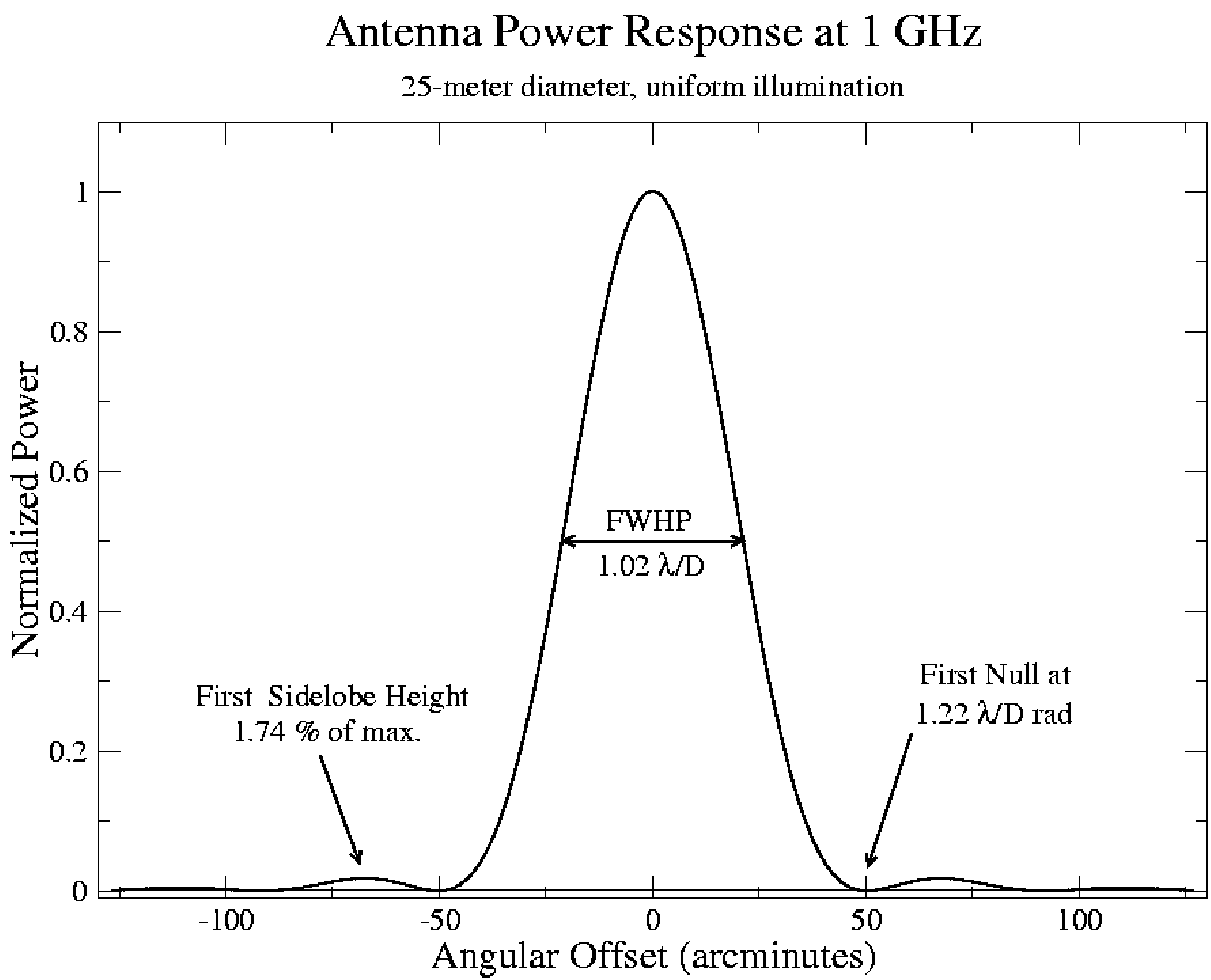


l = sin(θ), D = antenna diameter in λ

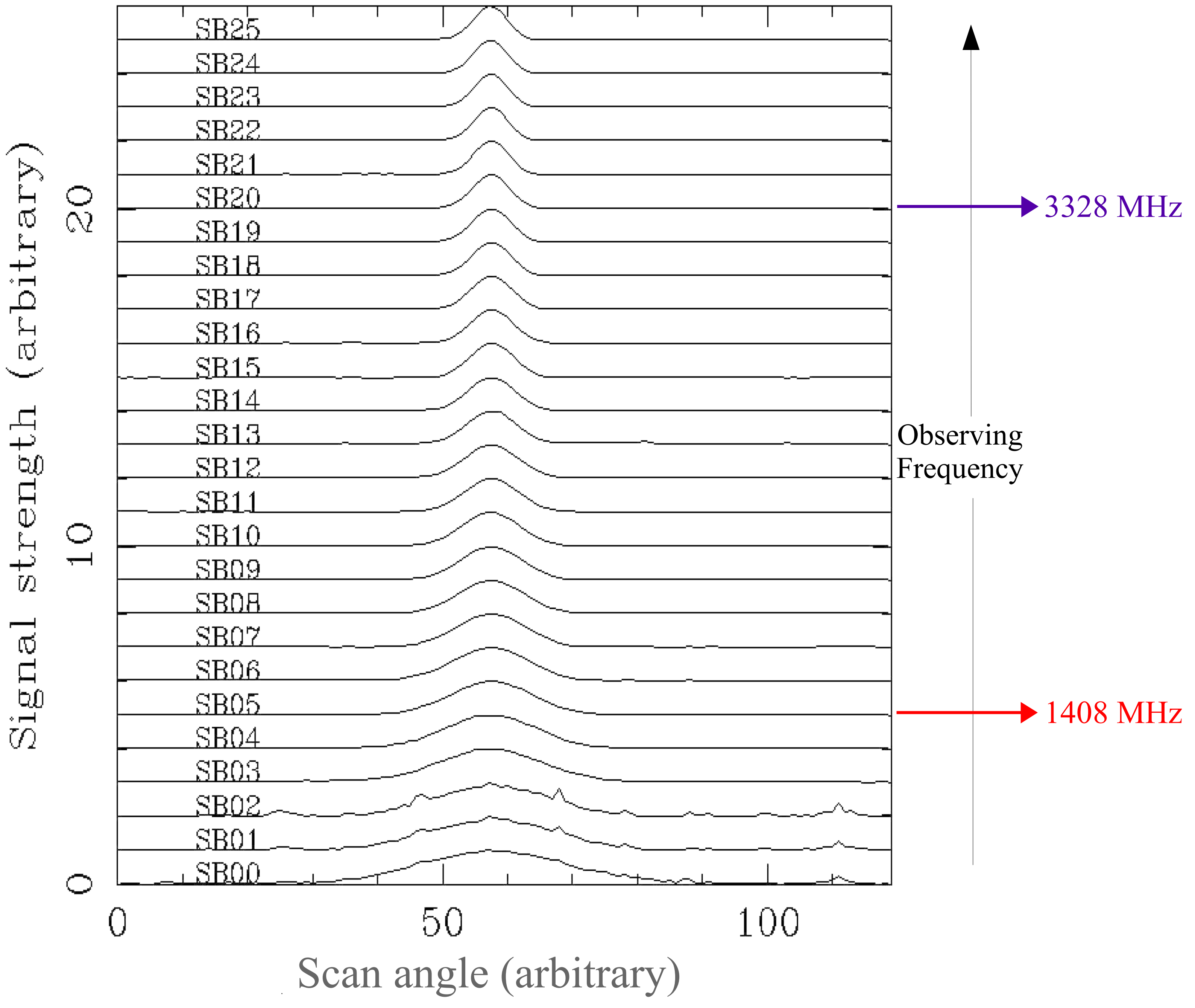
(contours:-3,-6,-10,-15,-20,-25,-30,-35,-40)

dB = 10 log(power ratio) = 20 log(voltage ratio)

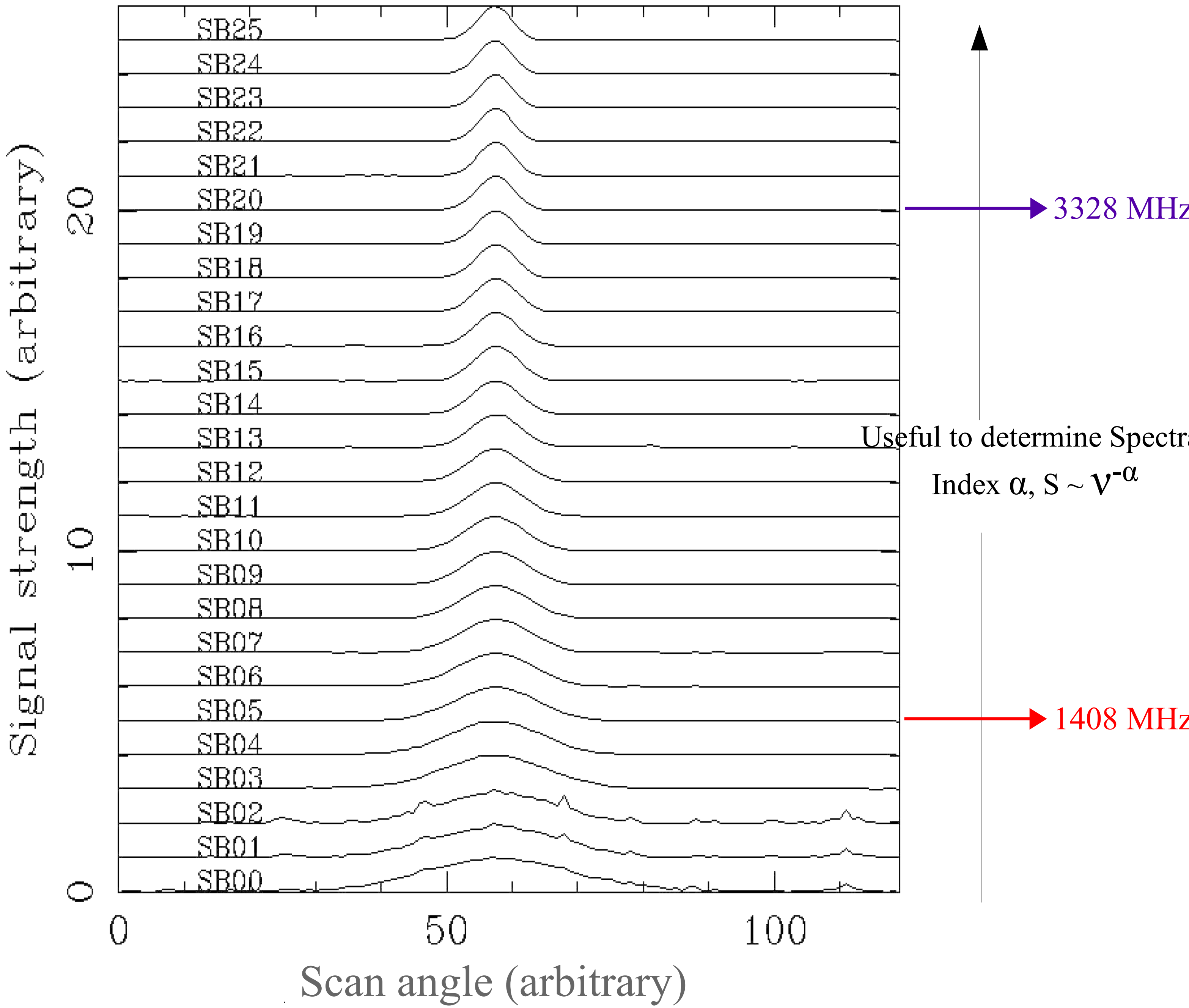
For VLA: θ_{3dB} = 1.02/D, First null = 1.22/D


Antenna Power Response at 1 GHz
25-meter diameter, uniform illumination
Normalized Power
0
0.2
0.4
0.6
0.8
1
-100
-50
0
50
100
Angular Offset (arcminutes)
FWHP
1.02 λ/D
First Sidelobe Height
1.74 % of max.
First Null at
1.22 λ/D rad

Parkes 64-m Antenna – Beam FWHM at different subbands

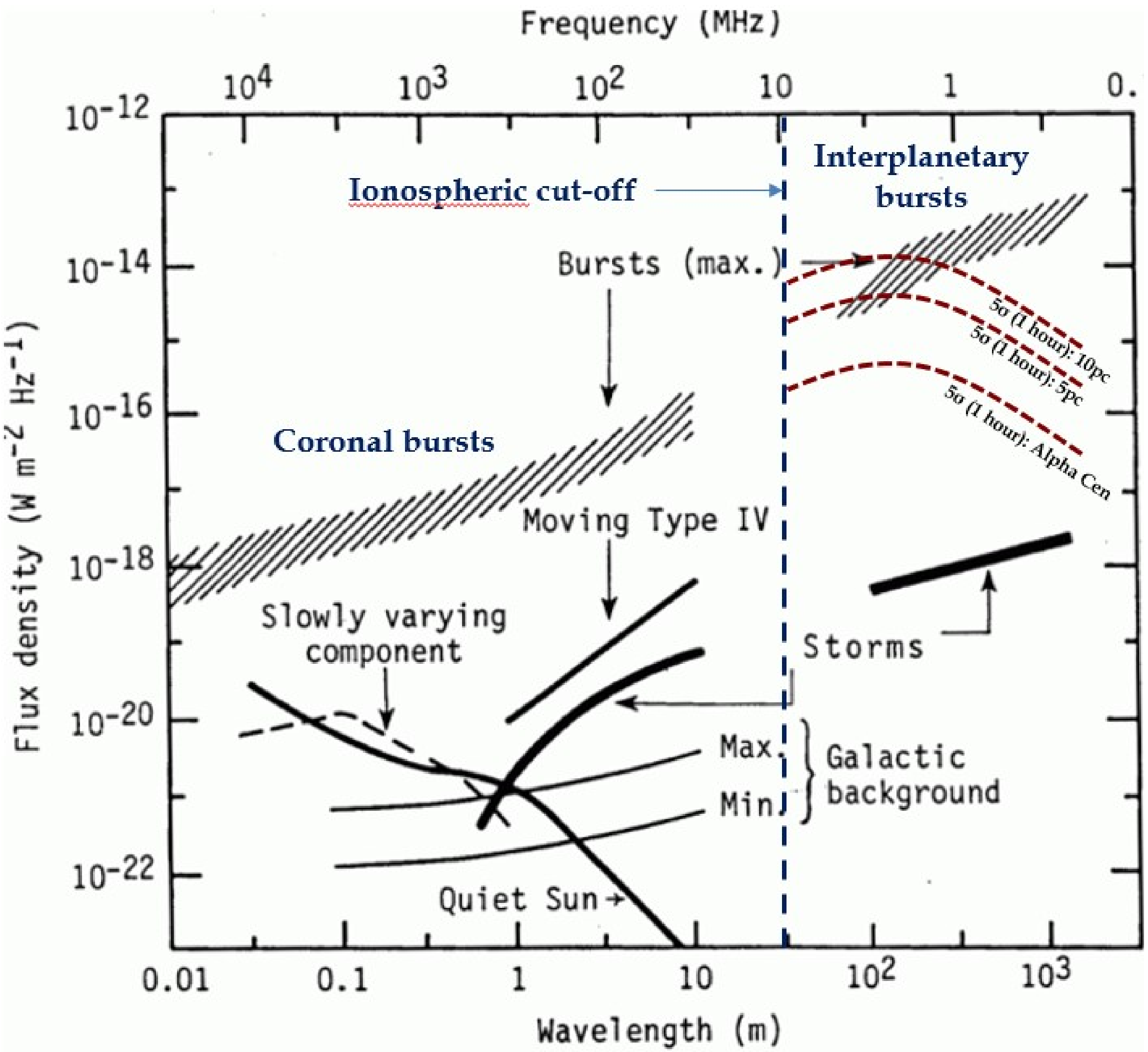


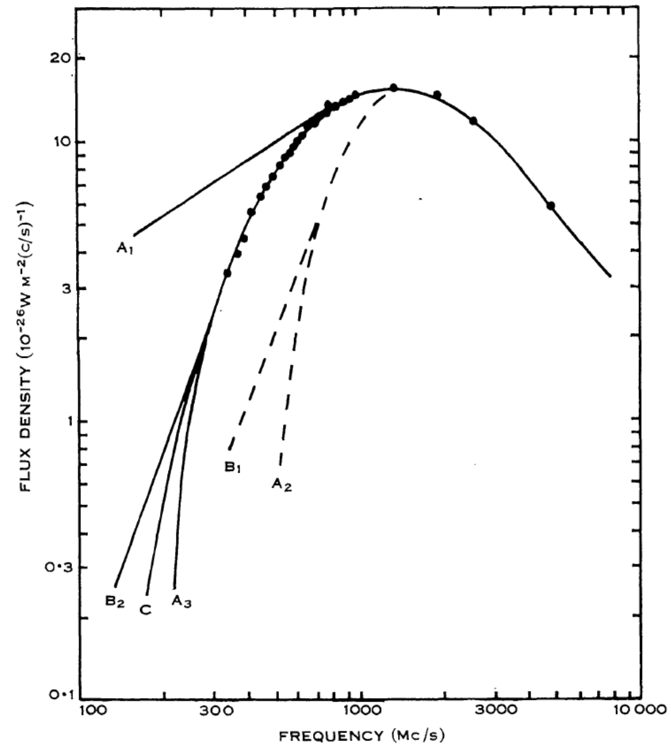
Parkes 64-m Antenna – Beam FWHM at different subbands



Useful to determine Spectral Index α, $S \sim \nu^{-\alpha}$

Solar Radio Measurements

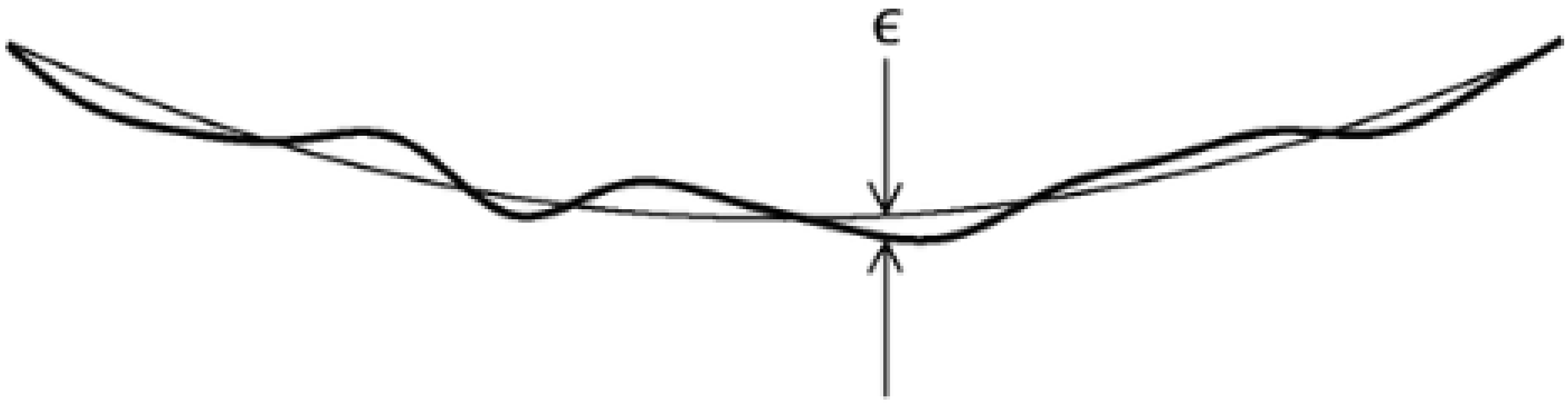




1934-63 (Kellermann 1966)

Pulsar profile broadening as a function of frequency gives scattering of the medium.

Non Ideal Parabolic Surface



Not-quite-perfect parabola

σ = rms surface error

Antenna surface accuracy (efficiency) can be affected by various factors.

Antenna Performance Parameters

Aperture Efficiency

$A_0 = \eta A$, $\eta = \eta_{sf} \times \eta_{bl} \times \eta_s \times \eta_t \times \eta_{misc}$

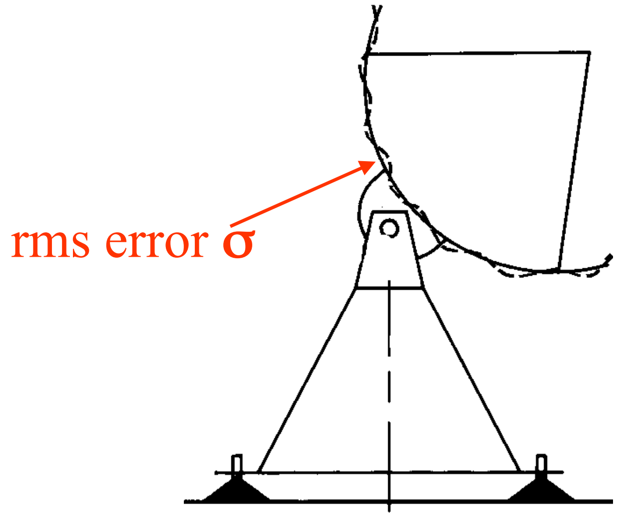
η_{sf} = reflector surface efficiency

η_{bl} = blockage efficiency

η_s = feed spillover efficiency

η_t = feed illumination efficiency

η_{misc} = diffraction, phase, match, loss



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

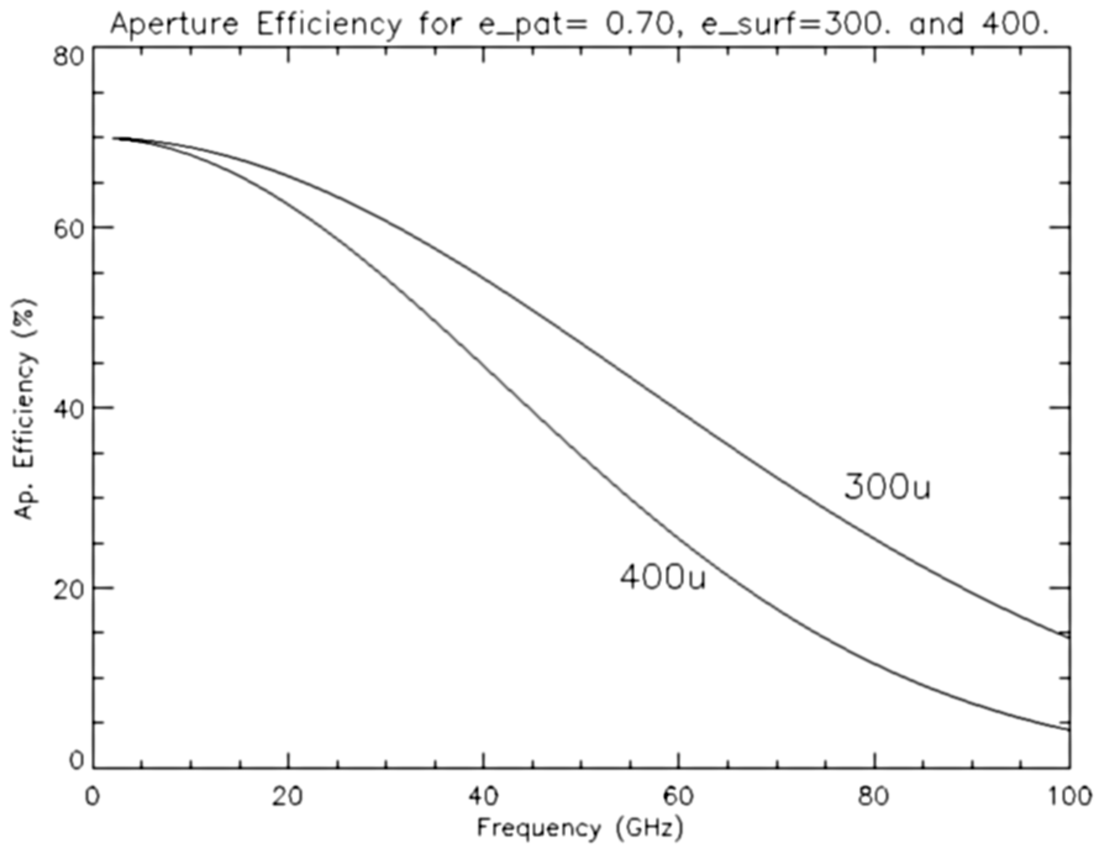
e.g., $\sigma = \lambda/16$, $\eta_{sf} = 0.5$

Surface roughness affects the antenna efficiency, which is a strong function of frequency.

Surface efficiency – Ruze formula

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

σ = rms surface error



Antennas rapidly lose performance at higher frequencies.

John Ruze of MIT -- Proc. IEEE vol 54, no. 4, p.633, April 1966.

Detectable Signal and System Temperature

Thermal noise ΔT
(minimum detectable signal)

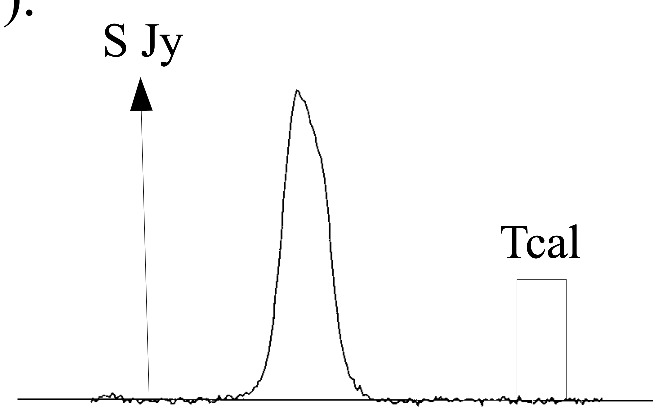
$$\Delta T = k_1 \frac{T_{sys}}{\sqrt{\beta \cdot t_{\mathrm{int}}}}$$

$$T_{sys} = T_{ant} + T_{Rx} + T_{CMB} + T_{spill} + T_{atm} \;\ldots.$$

total noise power detected, a result of many contributions

Telescope Gain is the antenna temperature, T_A, due to a point source of flux density 1 Jy at the peak of the telescope beam (G expressed in K/Jy).

System Equivalent Flux Density, SEFD = T_{sys}/G
(system noise given as flux density)



Thank You