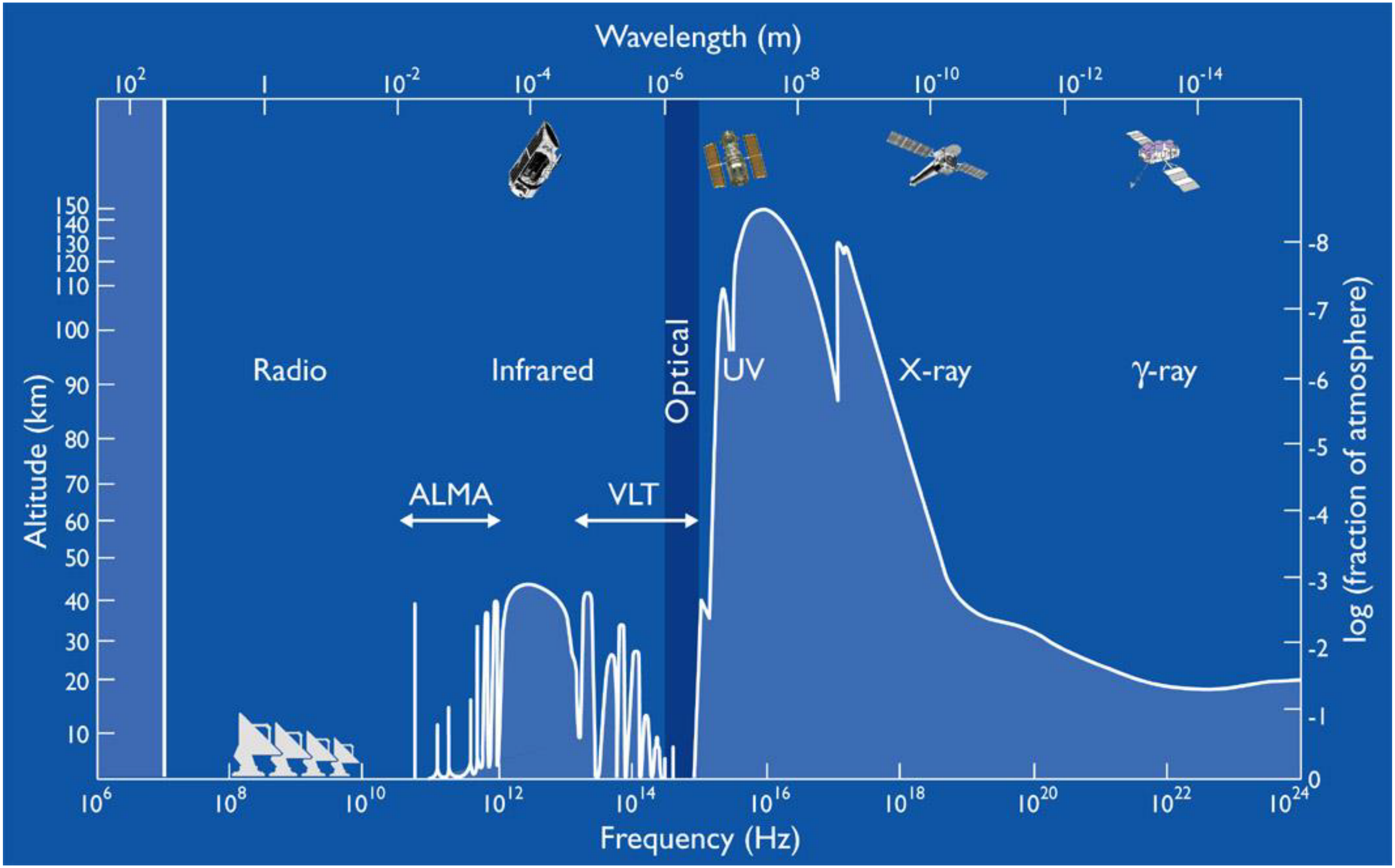
Antennas and Receivers in Radio Astronomy

Norbert Bartel

York University, Toronto

3rd Synthesis Imaging school in radio astronomy
Potchefstroom, near Johannesburg, 5 -11 July 2015

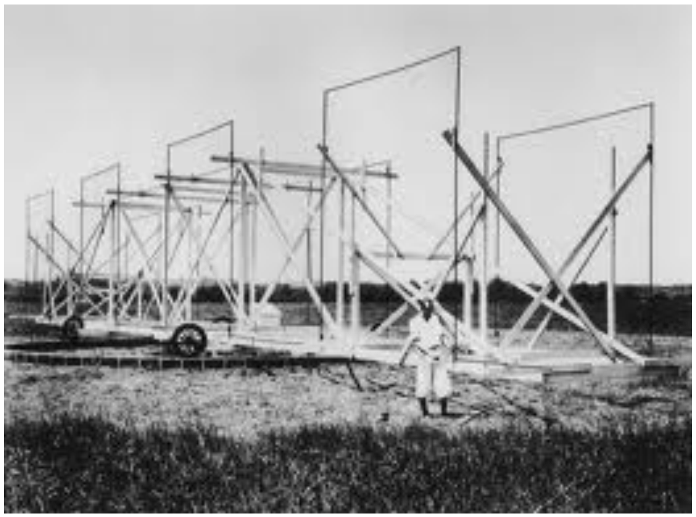
Atmospheric transparency of electromagnetic radiation



Outline

- History
- Antennas
  - Antenna types
  - Antenna characteristics
  - Antenna system as a 1-pixel camera
  - Feeds
- Receivers
  - Amplifiers, mixers, local oscillators
  - Sensitivity

Karl Jansky discovered radio waves coming from the Milky Way - 1932



Karl Jansky

Father of radio astronomy

1 Jansky= 10^{-26} W m^{-1} Hz^{-1}

He was working on atmospheric static at 3 – 30 MHz because this static hampered transatlantic radio telephony.

He found a source of radio emission with an "extraterrestrial origin." This radio emission came from the milky way.

Grote Reber
the first radio astronomer

Reflector antenna

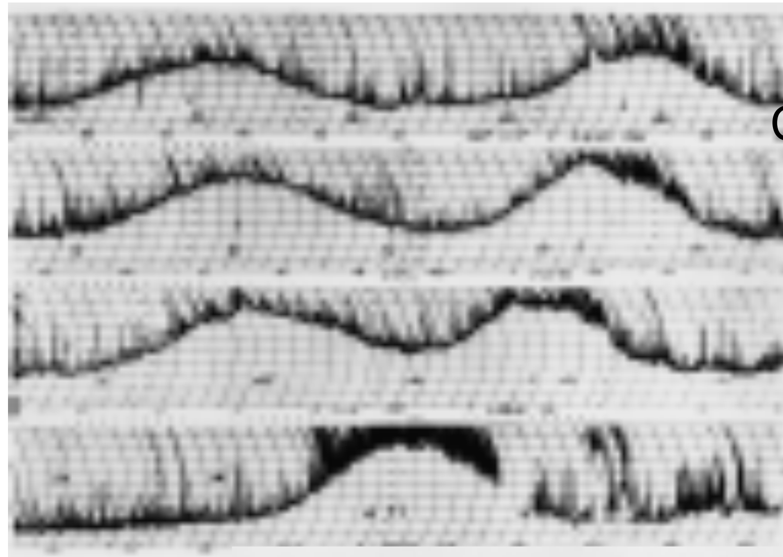


Chart recordings

Contour map of milky way

Nobel Prizes in Radio Astronomy

with different antenna designs

- Paraboloidal reflector
- Dipole array
- Horn antenna
- Spherical reflector

1974: Aperture Synthesis (Ryle) Pulsars (Hewish)

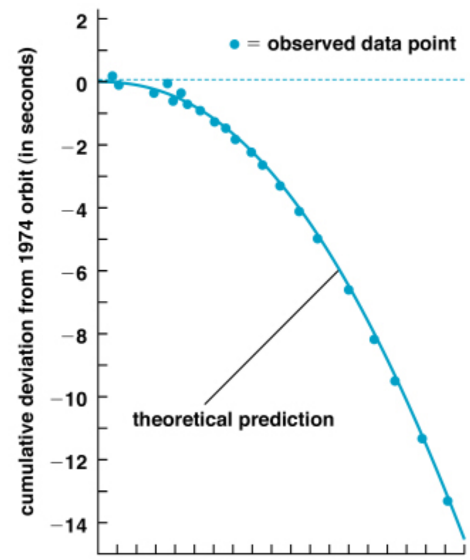
Element of 1 km array (MRAO)

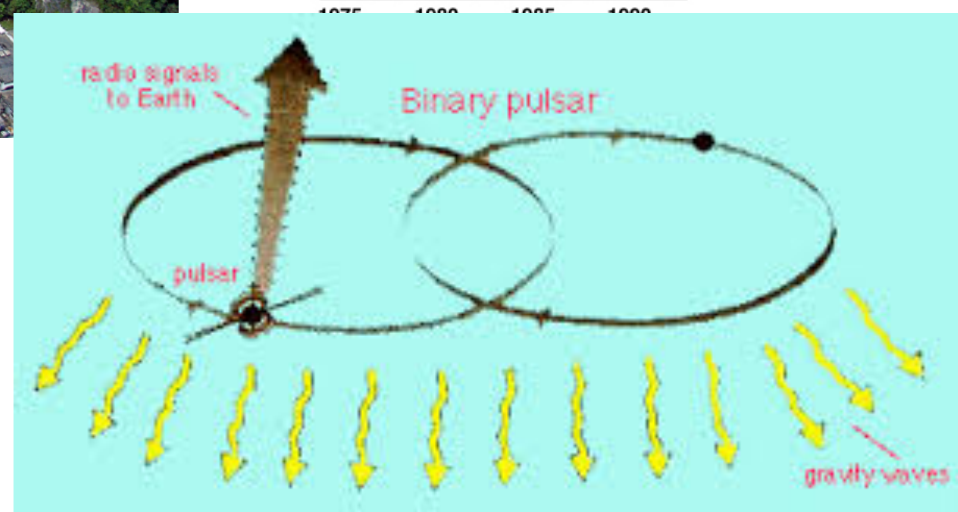
1978: Cosmic Microwave Background –CMB (Penzias and Wilson)

- 

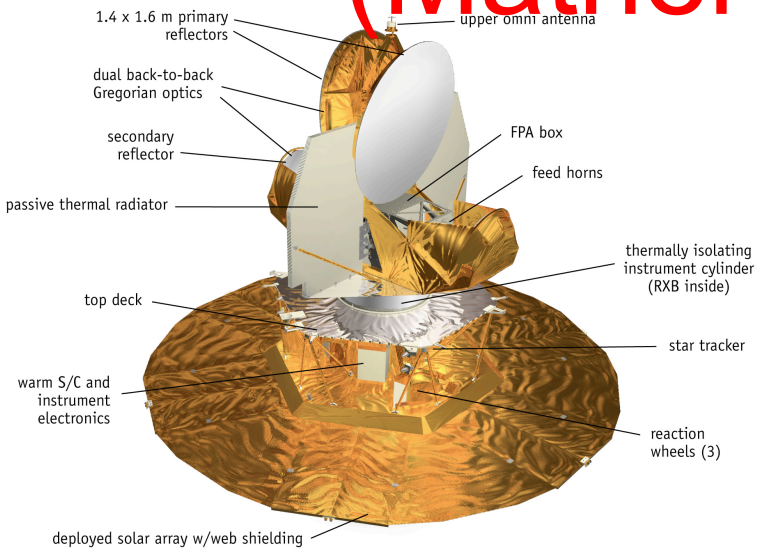
$T_{sky} = 2.7$ K

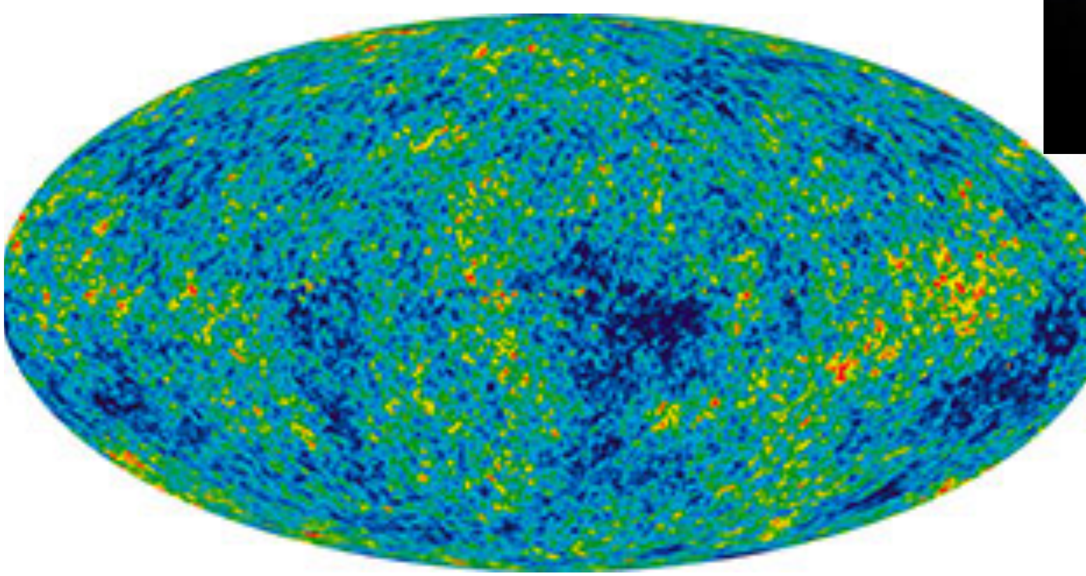
1993: Binary pulsar, gravitational studies (Hulse and Taylor)

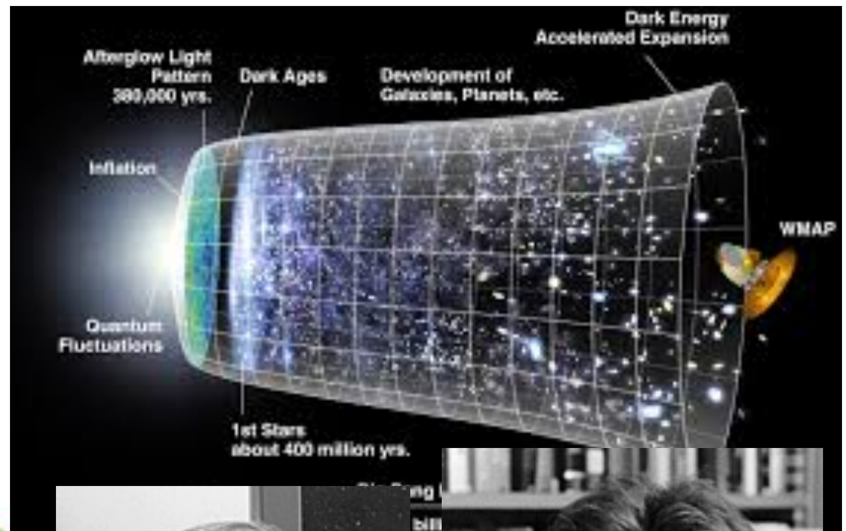


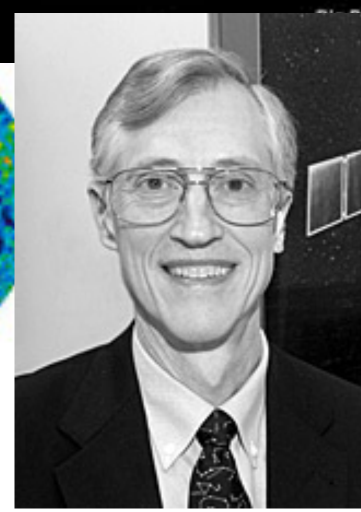


2006: WMAP
(Mather and Smoot)









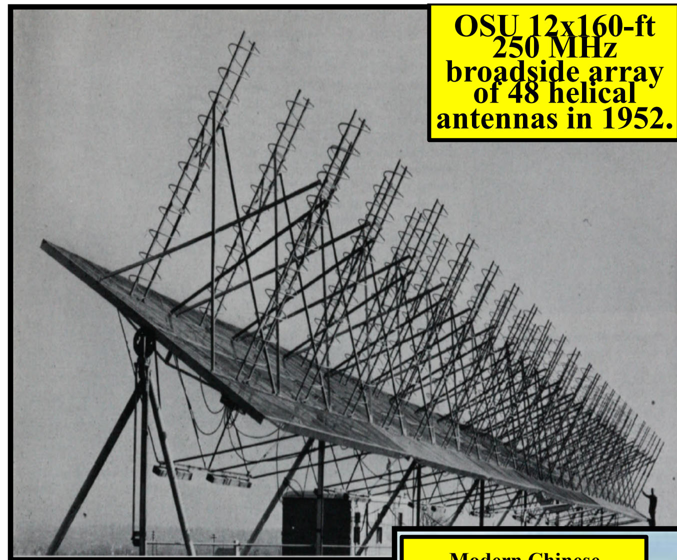
Antenna

- Track a source
- Gather the electromagnetic waves from the source over a large surface and focus the electromagnetic waves to a point
- Couple the free-space electromagnetic wave to an electromagnetic wave on the surface of a feed so that it can be amplified and digitized

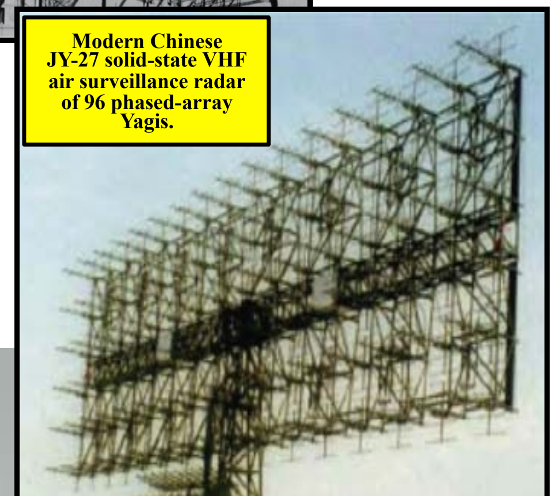
Types of Antennas

- Wire antennas $(\lambda > 1\mathrm{m})$
  - Dipole
  - Yagi
  - Helix

- Arrays of wire antennas
  - Broadside Arrays
  - Phased-Arrays
- Horn antennas $(\lambda < 1\mathrm{m})$
- Reflector antennas



OSU 12x160-ft 250 MHz broadside array of 48 helical antennas in 1952.



Modern Chinese JY-27 solid-state VHF air surveillance radar of 96 phased-array Yagis.

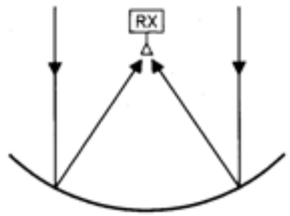
One of 7 telescopes of KAT-7

Horn antenna

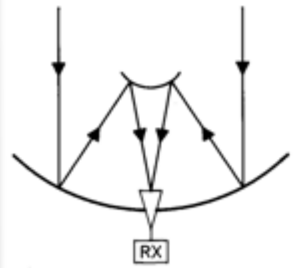
Partly B. Hayward NRAO Synthesis Imag. school

Examples of Antenna Reflector Optics

Prime Focus (GMRT)



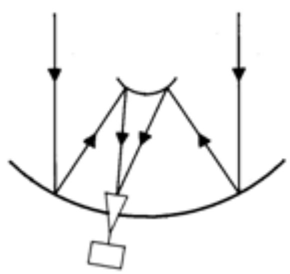
But: number of receivers limited,
Over-illumination causes increase in Tsys

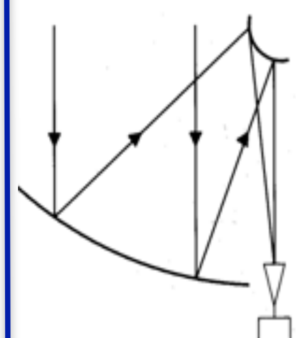


Cassegrain Focus (ATCA)

But: limited low frequency capability since feeds need to be large,
Over-illumination causes side lobes

Offset Cassegrain (JVLA)





Offset Gregorian (MeerKAT)

But: support structure can be complex and expensive,

Karoo Array Telescope
KAT 7

- MeerKAT precursor array
- 7 dishes of 12 m diameter
- Antenna type?

Karoo Array Telescope
KAT 7

- MeerKAT precursor array
- 7 dishes of 12 m diameter
- Prime focus reflecting telescope
- Largest baseline: 125 m
- Frequency range: 1200 to 1950 MHz

MeerKAT

- Meerkat precursor to SKA
- 64 dishes of 13.5 m diameter with 3.8 m subreflector
- Surface: σ=0.6 mm
- Longest baseline: 8 km
- Offset Gregorian reflecting telescope with 4 receivers
- Frequencies:

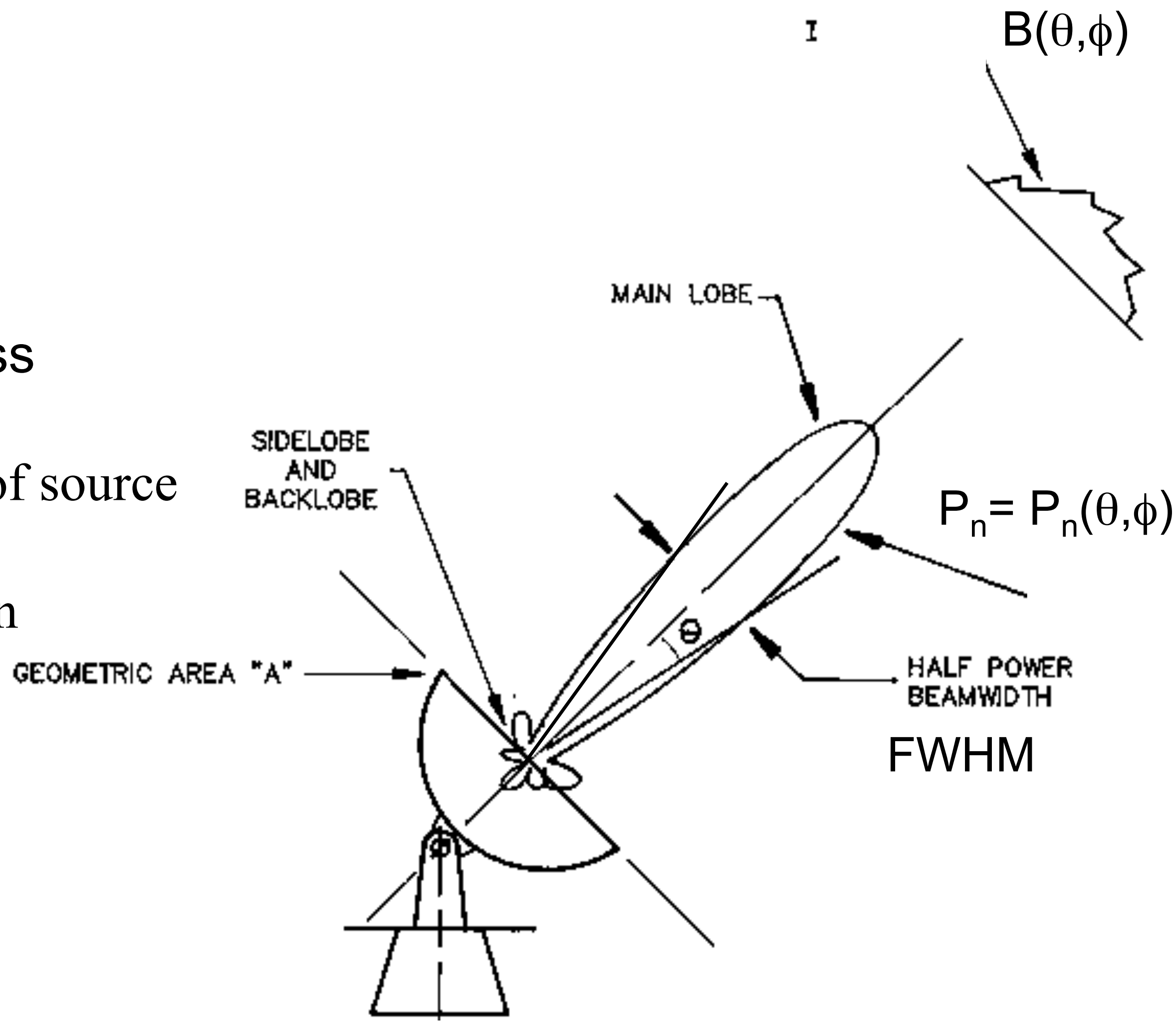
Reflector Antenna Characteristics

A: aperture
A_{eff} : effective aperture
η aperture efficiency
G gain
σ rms surface roughness
λ wavelength
B brightness distribution of source
P beam pattern
P_n normalized beam pattern

$P_n = P(\theta,\varphi)/P(0,0)$
$G = P(0,0) / P_{isotropic}$

$$G = \frac{4\pi}{\lambda^2} A_{eff}$$

$$A_{eff} = \eta \frac{\pi D^2}{4}$$

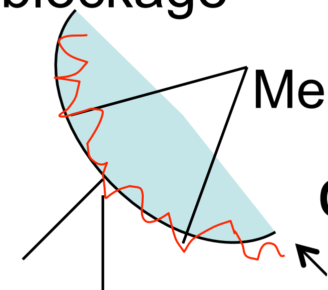


$\sigma < 0.05\lambda$ is needed

Reflector antenna efficiencies

$$\eta = \eta_{surface} + \eta_{def} + \eta_{blockage} + \eta_{illum} + \eta_{reflec} + \eta_{misc}$$

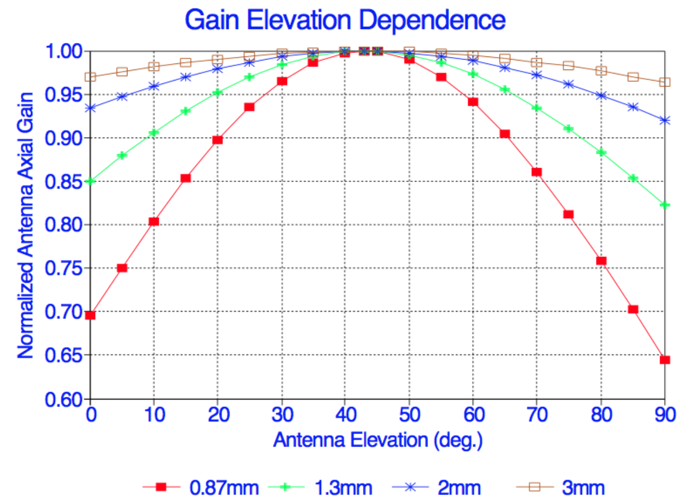
$$\eta_{surface} = e^{-\left(\frac{4\pi\sigma}{\lambda}\right)^2}$$



Meercat: σ = 0.6 mm, λ=2 cm,

σ

$\eta_{surface}$ =



η_{def} : due to elevation dependent deformation of antenna

$\eta_{blockage}$: due to blockage caused by feed legs and subreflector

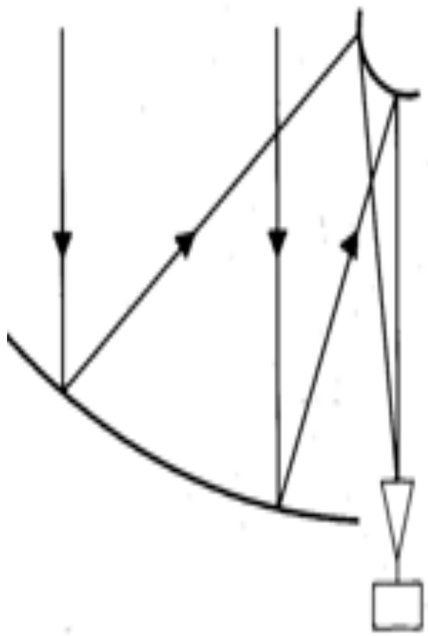
η_{illum} : due to spillover and taper (=0.8 for -10dB taper)

η_{reflec} : due to metal reflection efficiency (~99%)

η_{misc} : due to defraction, focus errors, polarization aspects

Offset design

no blockage



Offset

Gregorian

GBT

MeerKAT

Decibels (dB's)

Decibels are used in engineering language to express amplification or attenuation

An amplification of x dB: a change of $10^{+0.1x}$

An attenuation of x dB: a change of $10^{-0.1x}$

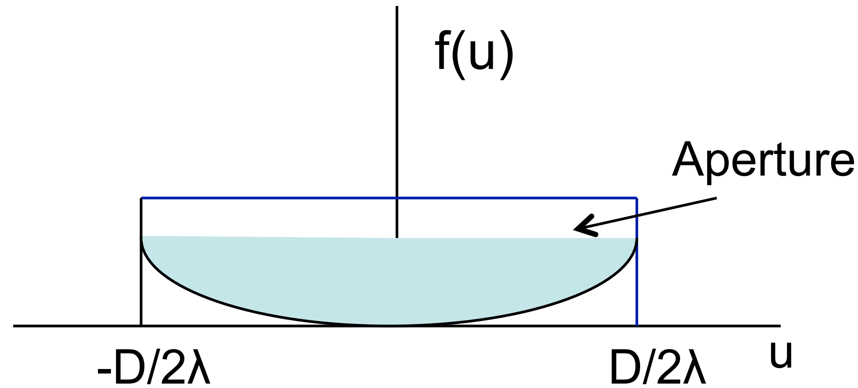
change of 3 dB → 2 times, -3 dB → 0.5 times

change of 10 dB → 10 times, -10 dB → 0.1 times

change of 30 dB → 1,000 times, -30 dB → 0.001 times

The antenna beam pattern

$f(u,v)$ = complex aperture field distribution
u,v = aperture coordinates (in λ)



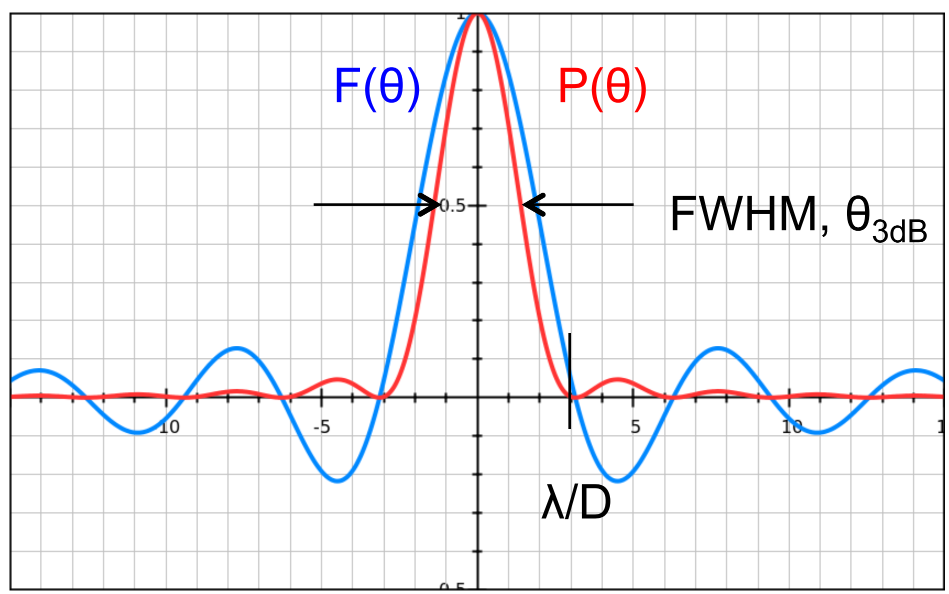
$F(l,m)$ = complex far-field voltage pattern
$l = \sin\theta\cos\varphi$, $m = \sin\theta \sin\varphi$

$F(l,m) = FT\{f(u,v)\}$

$P(l,m) = F(l,m)^2$

FWHM ~ 0.88 λ/D [rad] square aperture
FWHM ~ 1.2 λ/D [rad] round aperture

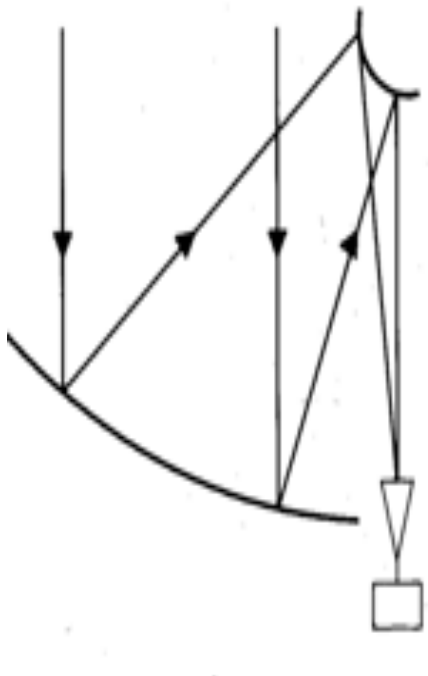
For HART, D=25m, λ = 3.6 cm:
FWHM = 6 arcmin



For rectangular aperture

Offset design

no blockage



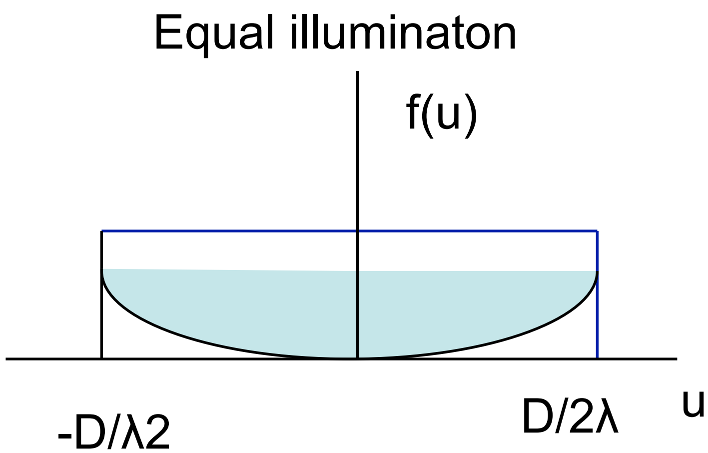
Offset Gregorian

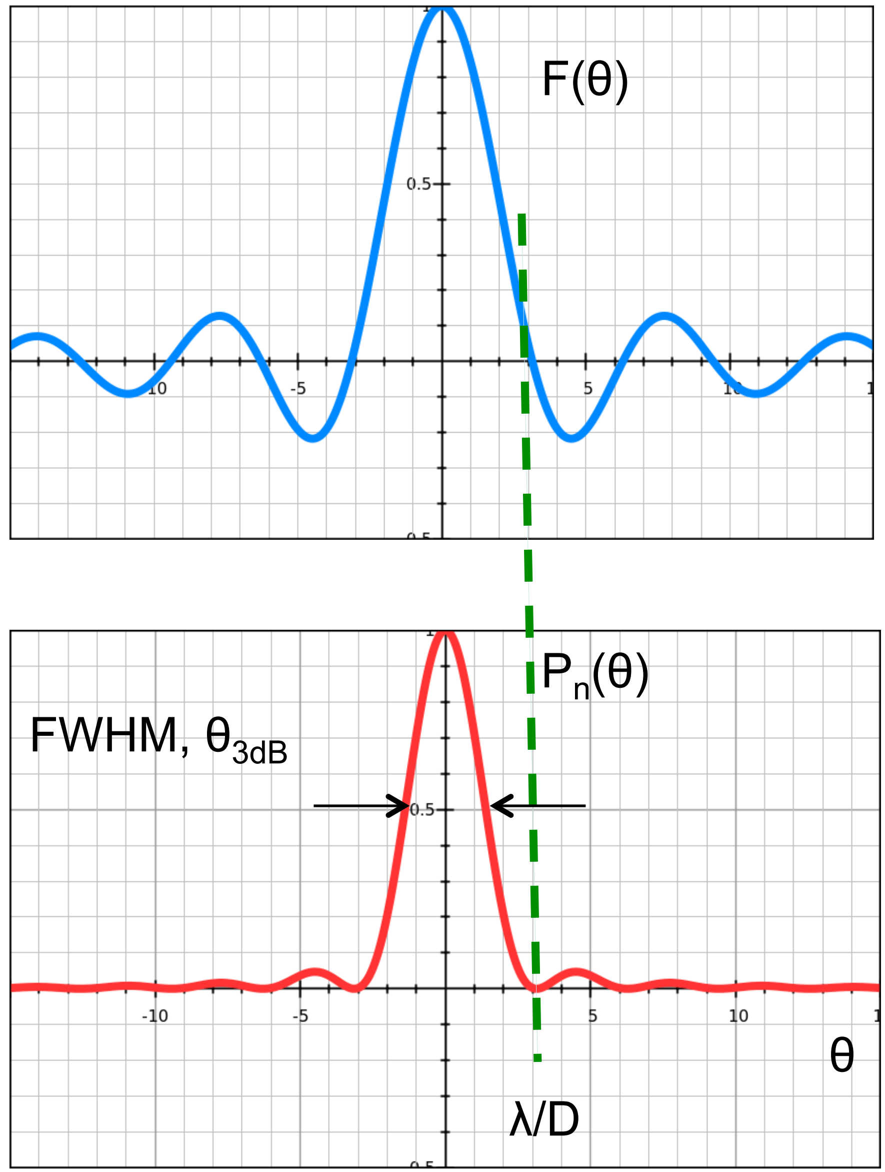
GBT

MeerKAT

Tapering

less illumination to the outer parts of the aperture



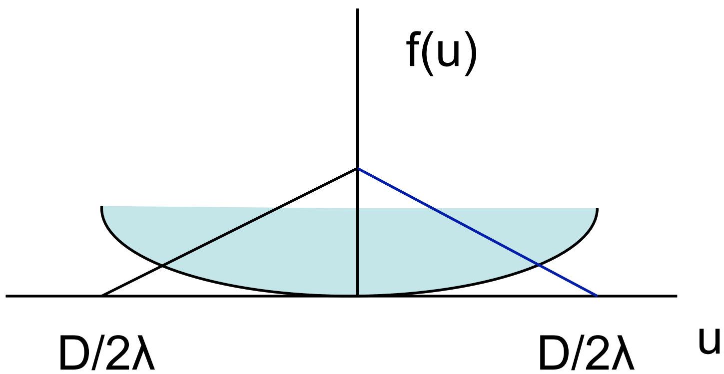


Gate function: $f(u) = \Pi(u)$

$\Pi(u) \leftrightarrow \text{sinc}(l)$

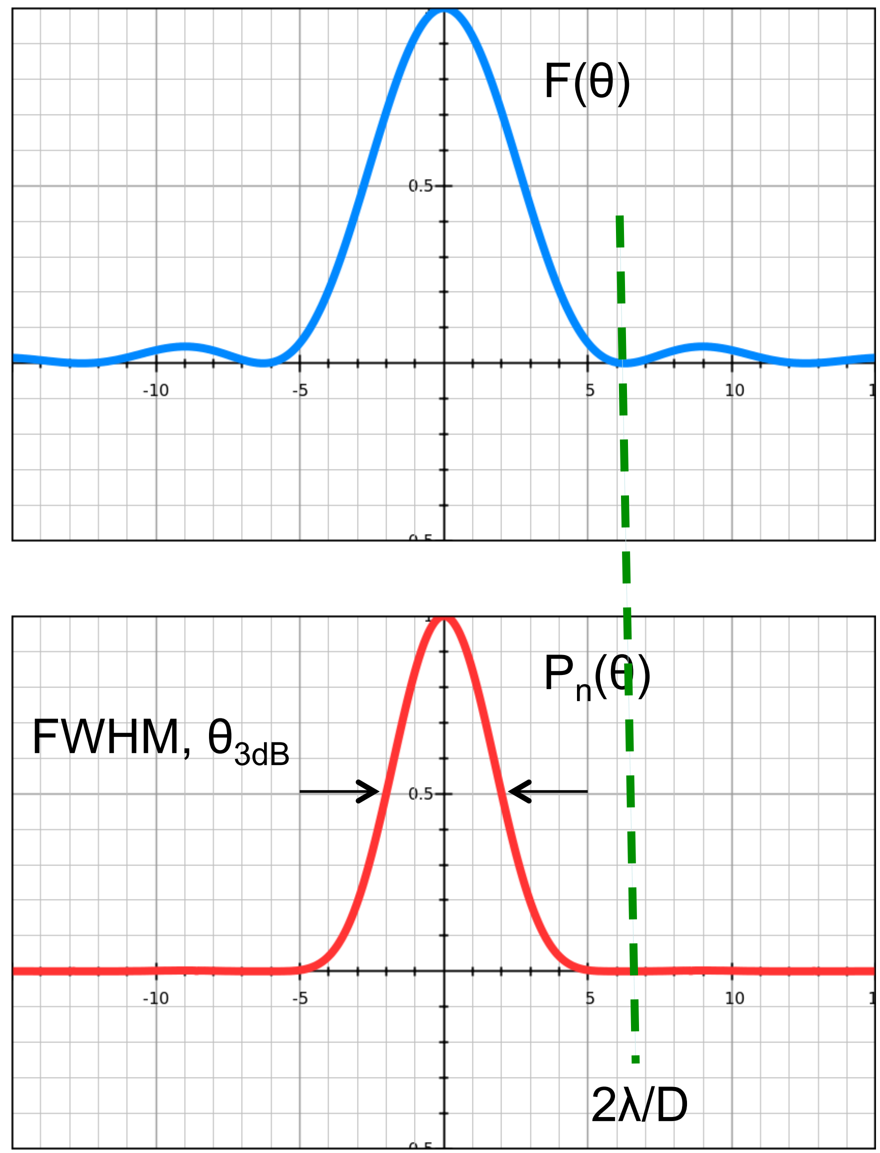
$\leftrightarrow$:Fourier transform pair

Less illumination
toward outer parts of aperture

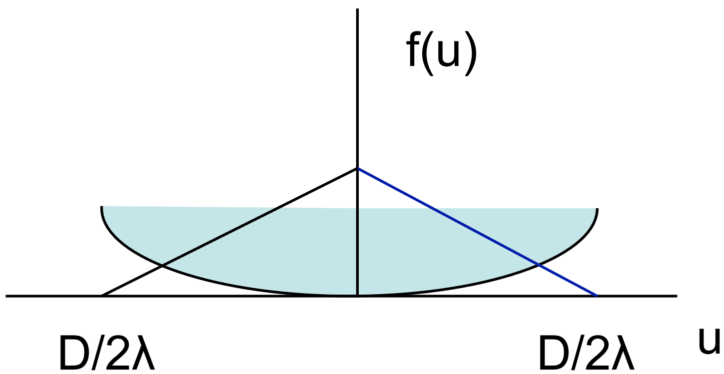


$f(u) = \Pi(2u) * \Pi(2u)$

$\Pi(2u) * \Pi(2u) \Leftrightarrow \mathrm{sinc}^2(l/2)$



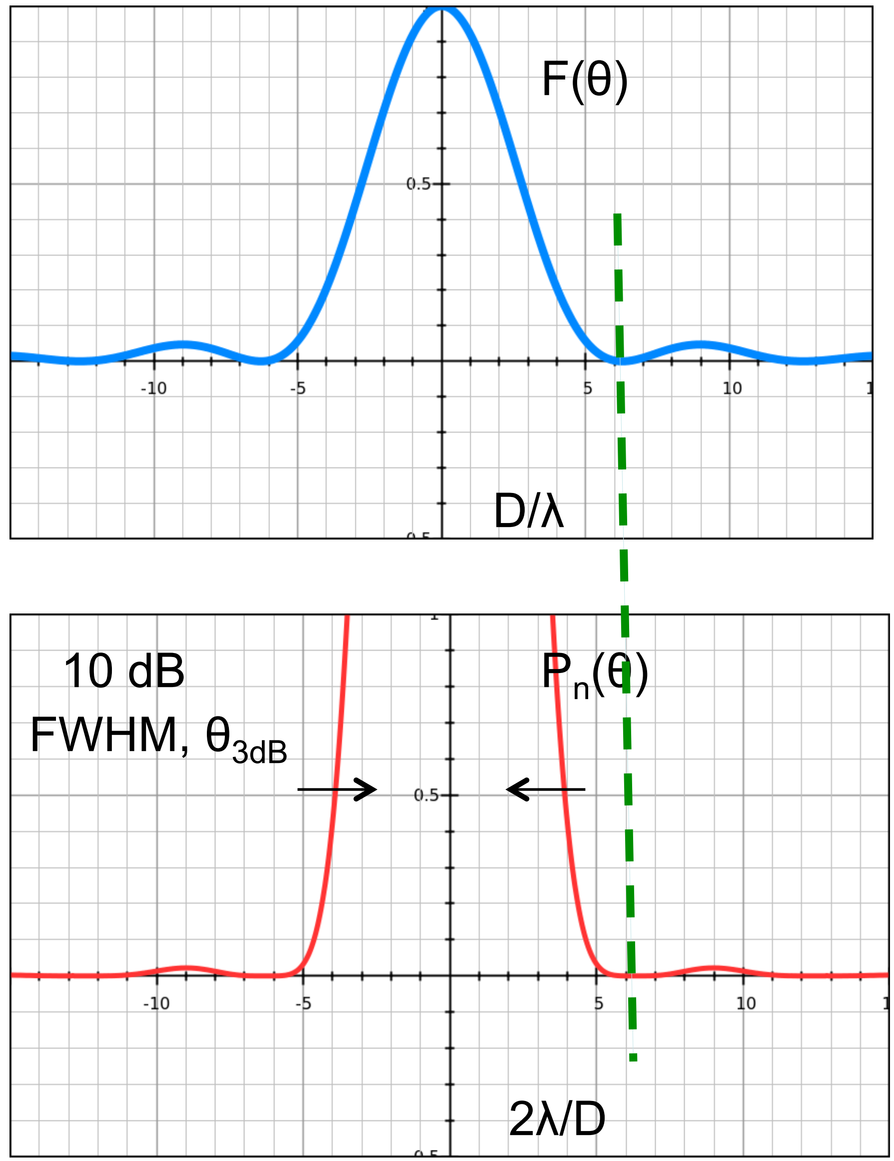
Less illumination
toward outer parts of aperture



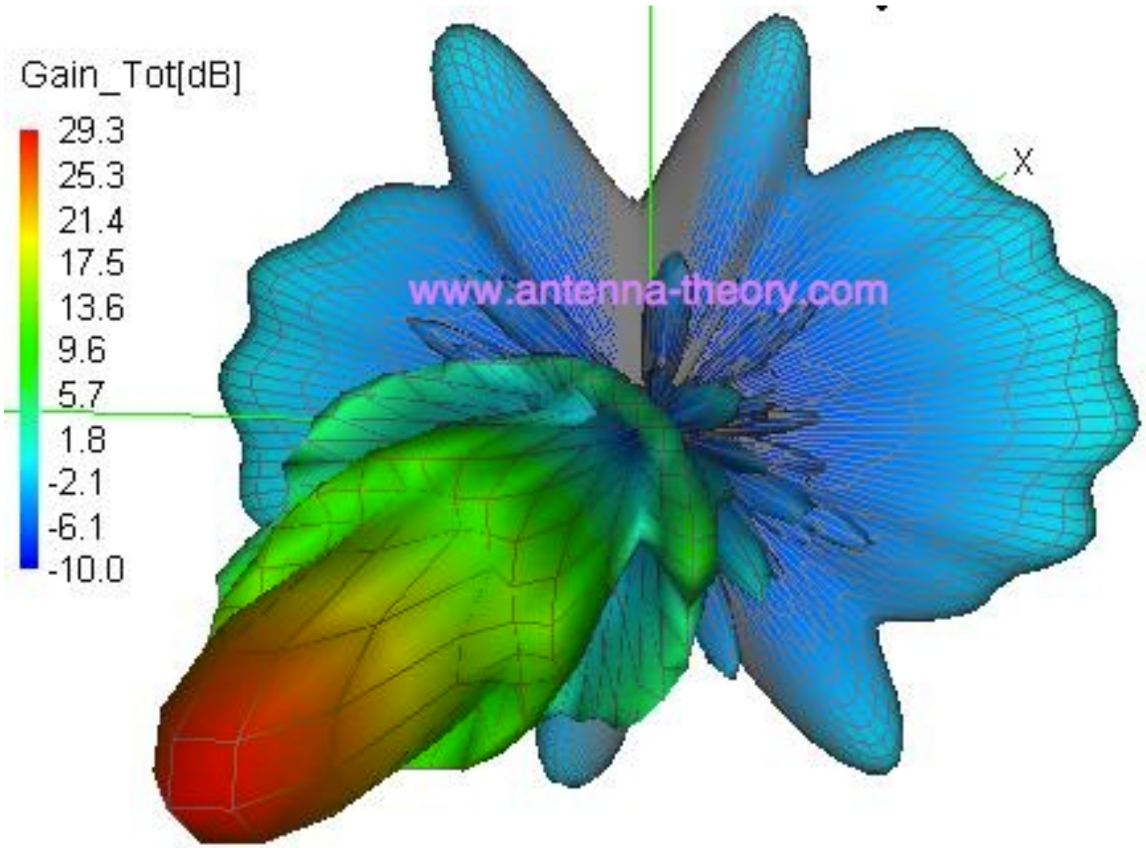
$f(u)= \Pi(2u) * \Pi(2u)$

$\Pi(2u) * \Pi(2u) \Leftarrow\Rightarrow \mathrm{sinc}^2(l/2)$

Tapering lowers sidelobes
and increases beam width



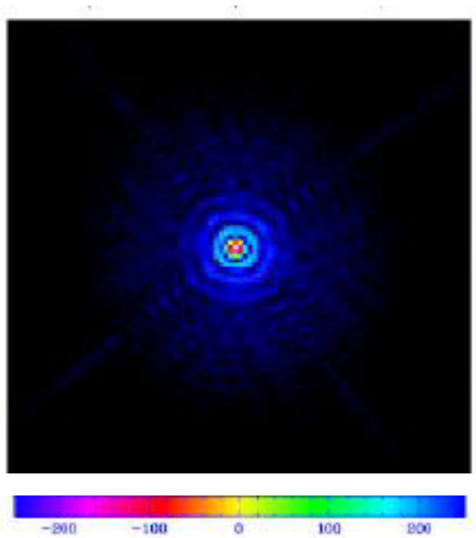
Realistic 3-dim beam pattern



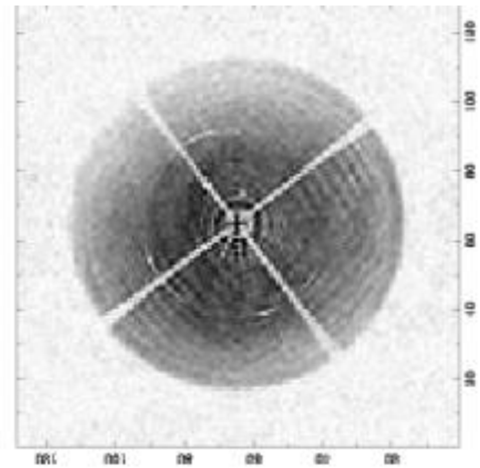
Holography

a technique of measuring the complex beam pattern, $P_n(\theta)$, and obtaining the complex aperture illumination, $f(u)$, through inverse Fourier transform

Beam pattern



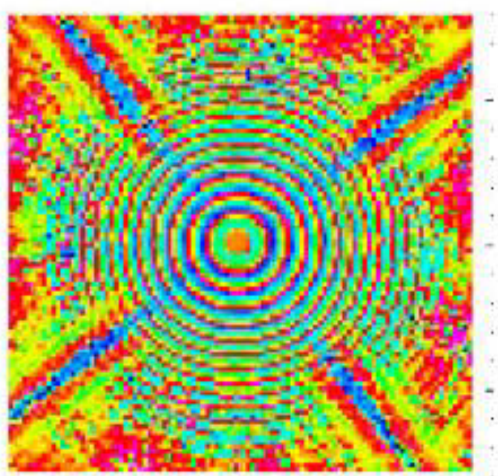
Aperture

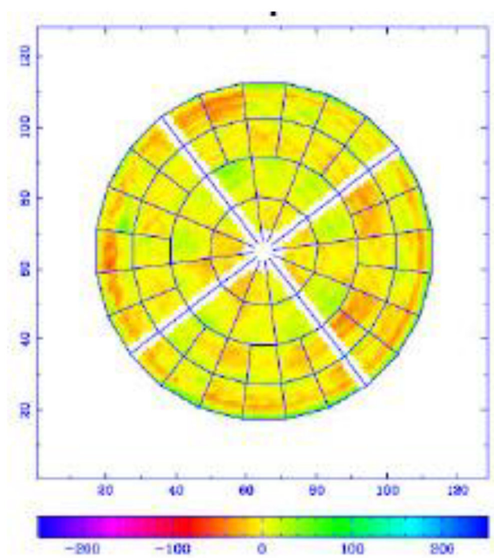


Amplitude

Fourier transform pairs

Phase





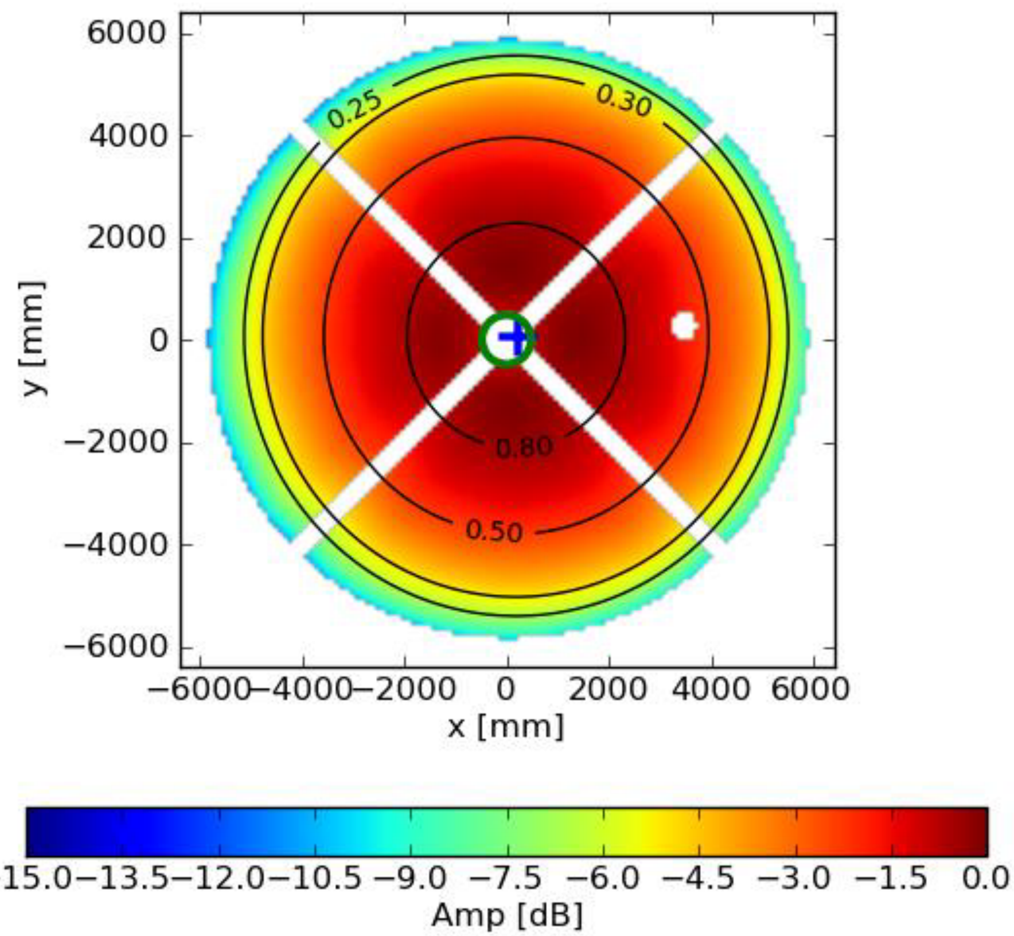
Aperture - amplitude
Example: ALMA

-10 dB taper

Good compromise between

1) Beam size, $\theta_{3dB} = 1.13\ \lambda/D$
2) Sidelobes: -23 dB
3) Illumination efficiency, $\eta_{illum} = 0.8$

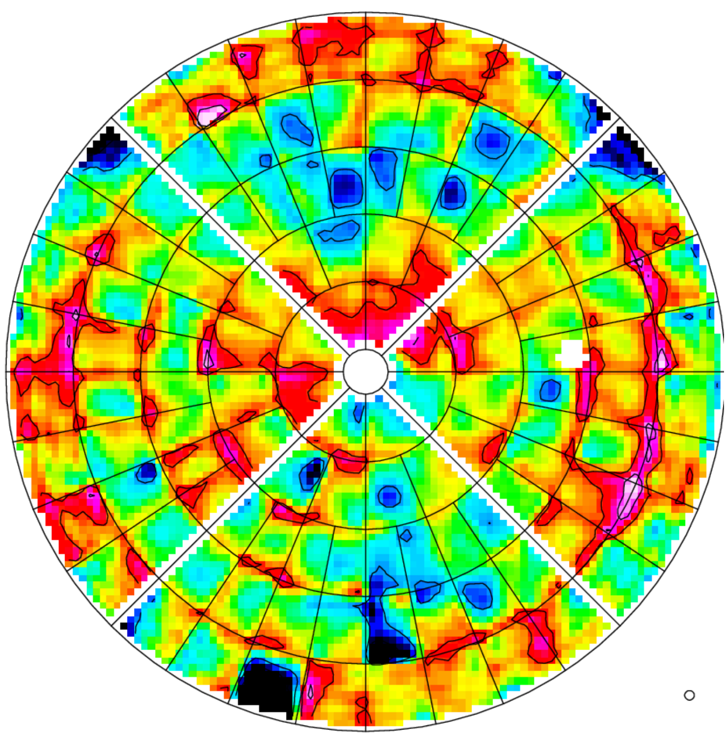
Tapered antenna illumination



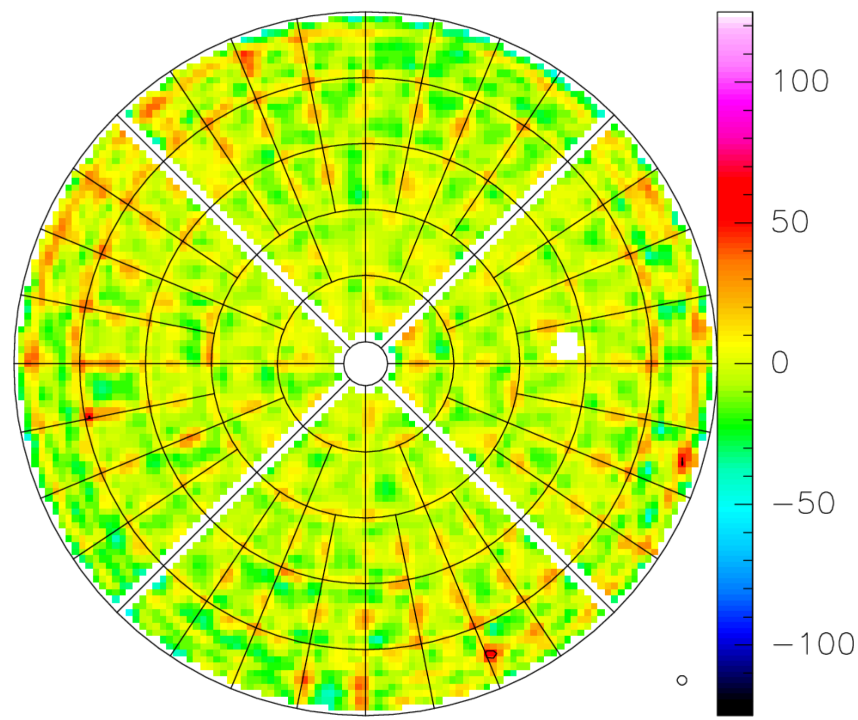
Aperture - phase
Example: ALMA

Phase translated to path length errors with respect to a perfect paraboloid
➔ Surface smoothness can be improved

Before adjustment, σ=43 μm

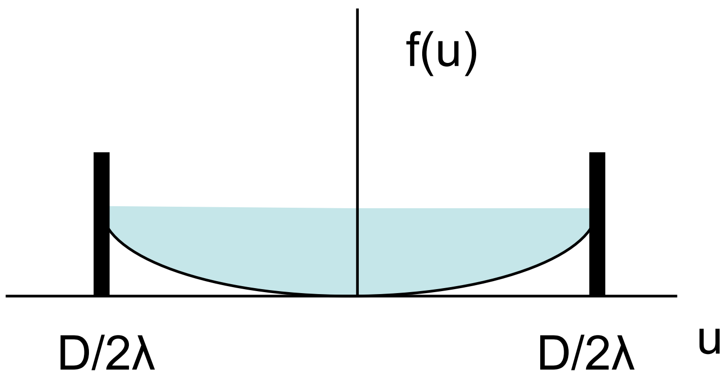


After adjustment, σ=11 μm



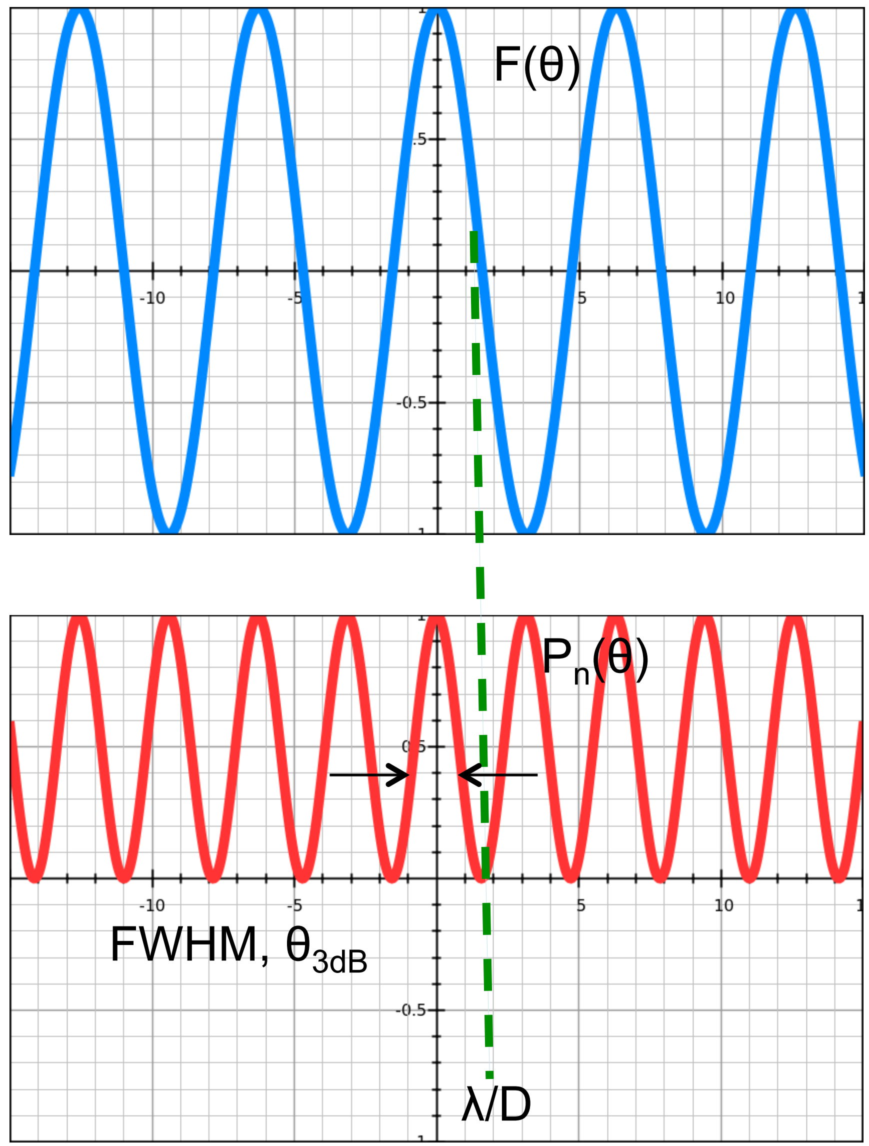
Extreme inverse Tapering

only illumination
at the outer parts of the aperture



$$f(u) = 0.5(\delta(u+D/2\lambda)+\delta(u-D/2\lambda))$$

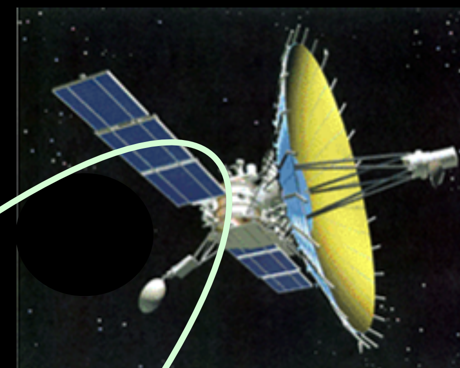
$$0.5(\delta(u+D/2\lambda)+\delta(u-D/2\lambda)) \leftrightarrow \cos(2\pi l D/2\lambda)$$



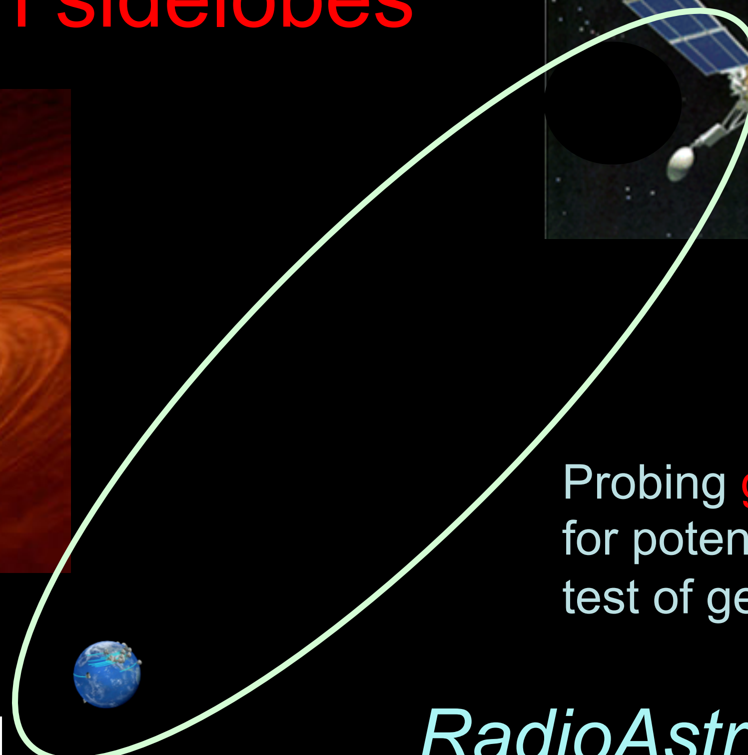
Huge sidelobes
and smallest possible
beam width

Largest “diameter” of a synthesized telescope: D=300,000 km

Super-high angular resolution
but also very high sidelobes



H-clock-2



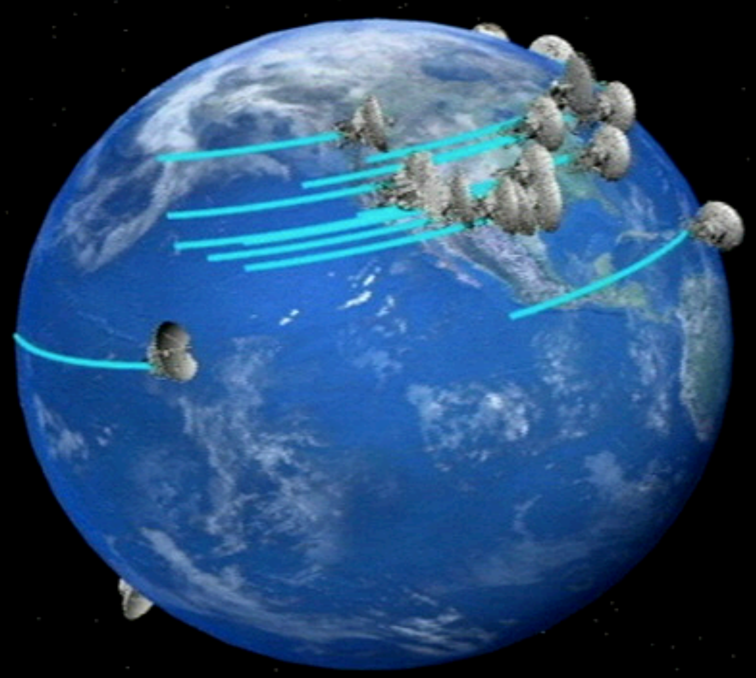
Probing gravitational redshift
for potentially most sensitive
test of general relativity

H-clock-1

RadioAstron
Ground-space VLBI mission

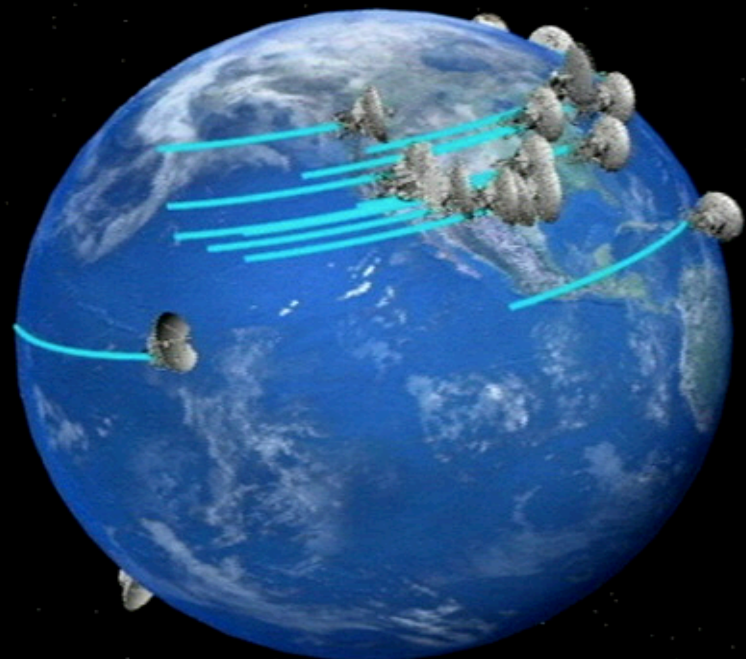
RadioAstron

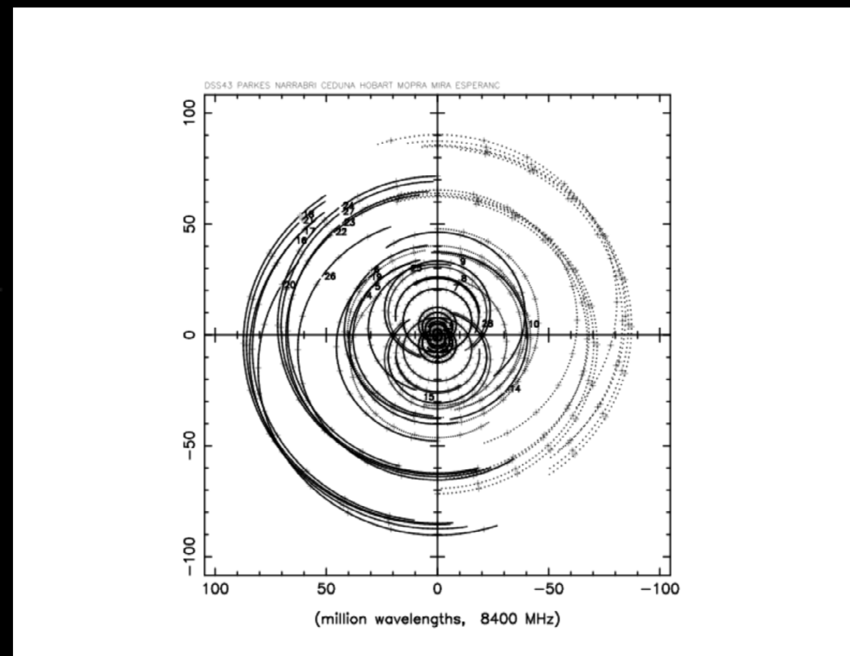
VLBI



Max baseline: 10,000 km
D=10,000 km
λ = 1.3 cm
FWHM = 0.3 mas

VLBI





Max baseline: 10,000 km
D=10,000 km
λ = 1.3 cm
FWHM = 0.3 mas

Antenna pointing and tracking

Static pointing errors

Blind pointing without nearby pointing calibrator

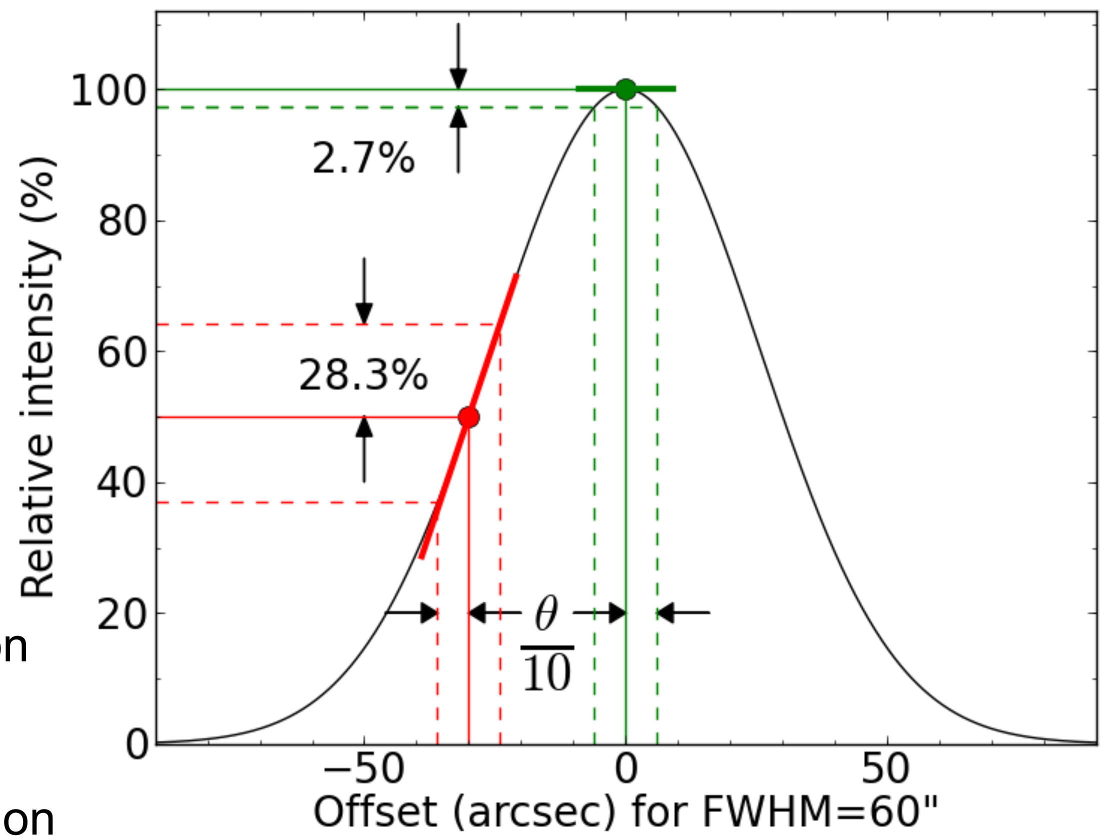
Dynamic pointing errors

Tracking errors due to wind etc.

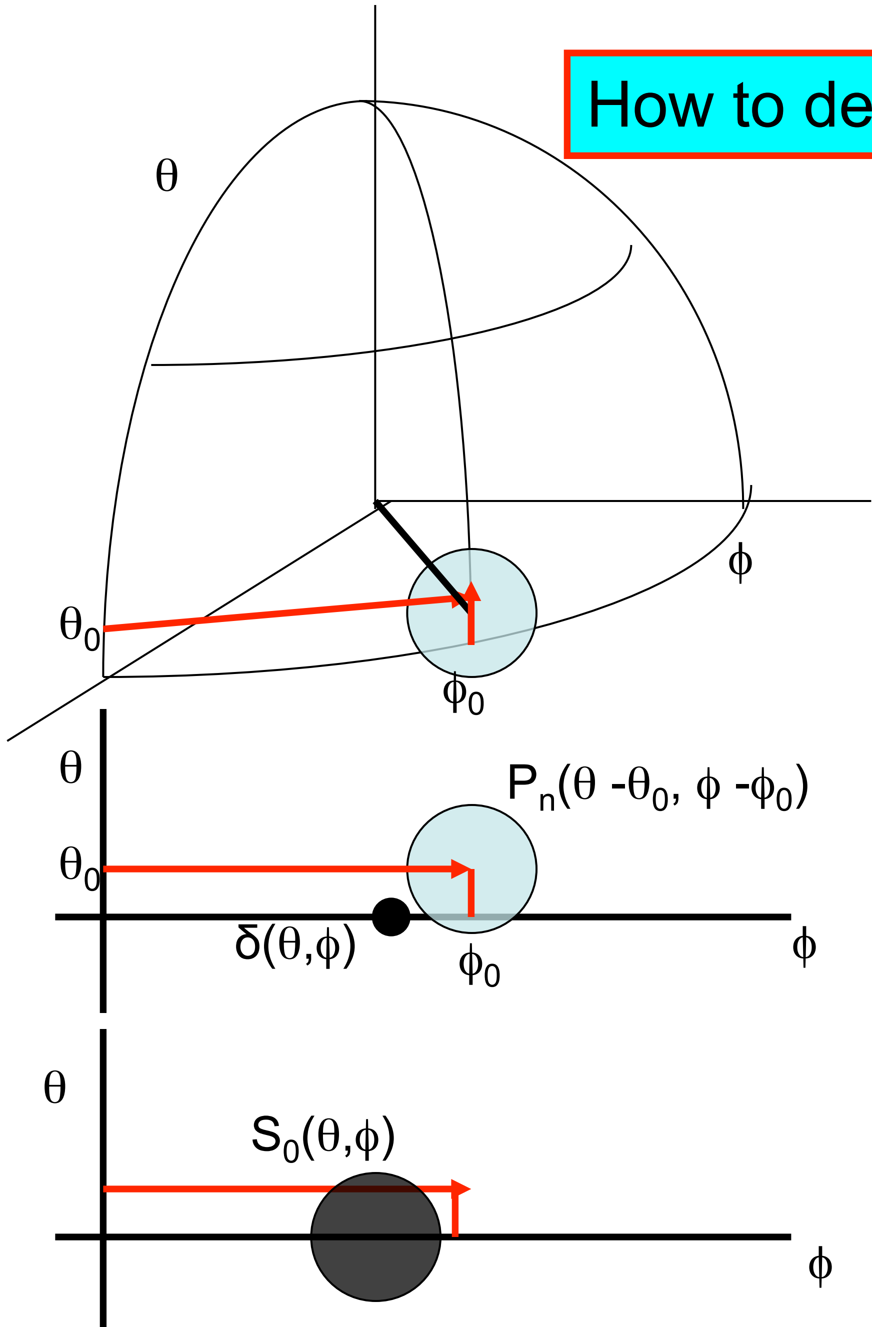
If pointing correct within FWHM/10

At 0 arcsec offset:
➔ 2.7% measured intensity variation

At HWHM point:
➔ 28.3% measured intensity variation



How to determine the beam pattern?



$P_n(\theta,\phi)$ Beam pattern (FWHM), (normalized to 1)

$P_n(\theta - \theta_0, \phi - \phi_0)$ Beam pattern (FWHM) at pointing position, (θ_0,ϕ_0)

$A\delta(\theta,\phi)$ Brightness distribution of point source at position θ_0,ϕ_0

$S_0(\theta_0,\phi_0)$ Measured flux density at pointing position, (θ_0,ϕ_0)

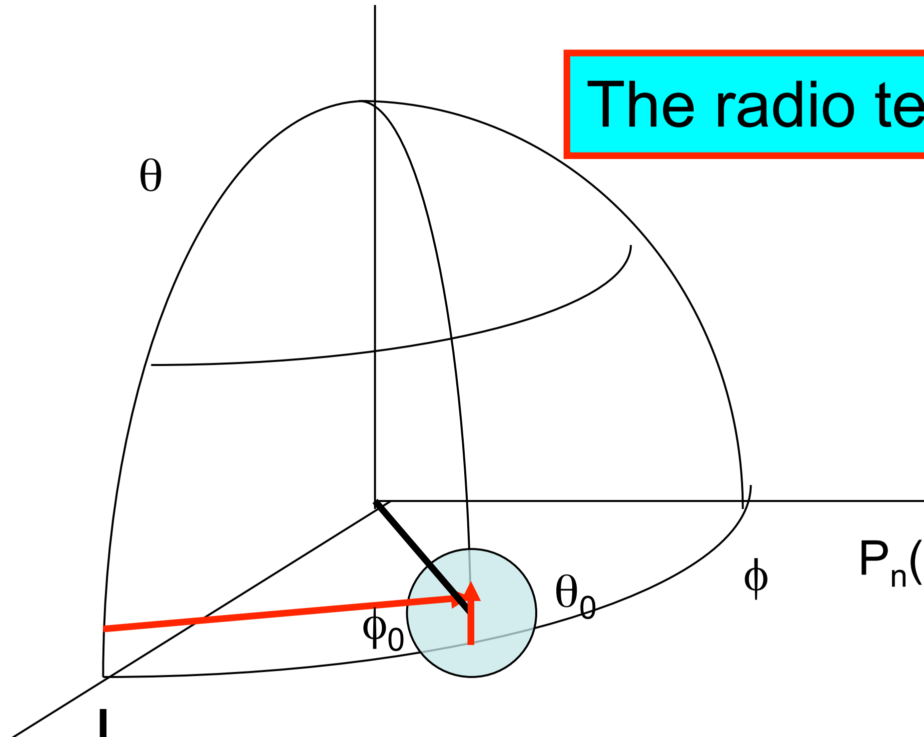
$$S_0(\theta_0,\varphi_0) = A\int \delta(\theta,\varphi) P_n(\theta-\theta_0,\varphi-\varphi_0)\, d\varphi d\varphi$$

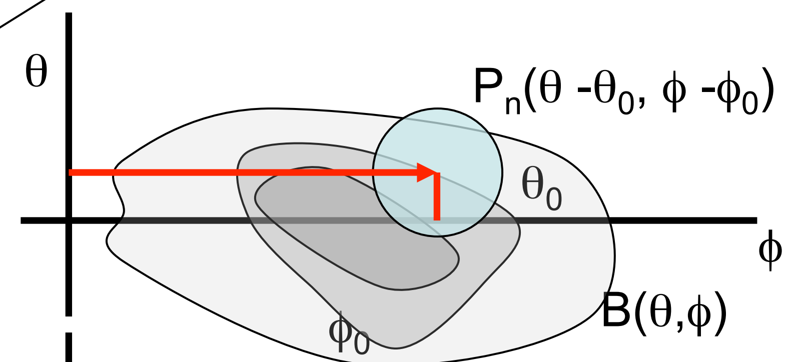
$$S_0 = A(\delta * P_n)$$

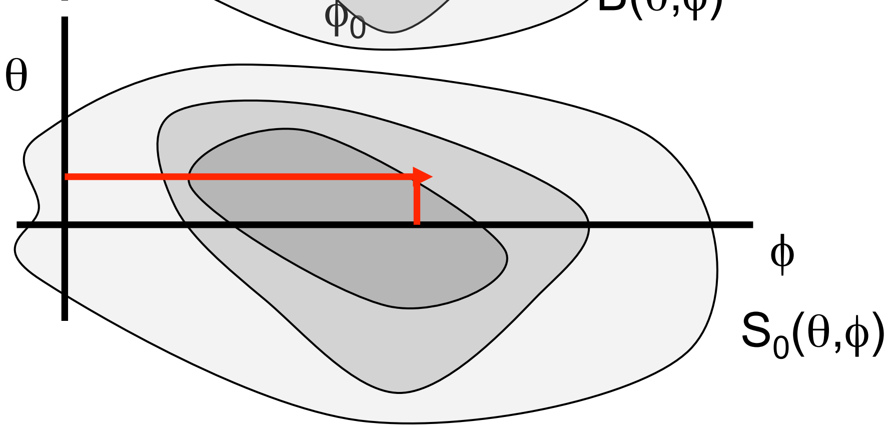
$S_0(\theta,\phi)$: shape of beam pattern

Scanning a point source gives the beam pattern (amplitude)

The radio telescope as a 1-pixel camera







$P_n(\theta,\phi)$ Beam pattern (FWHM), (normalized to 1)

$P_n(\theta - \theta_0, \phi - \phi_0)$ Beam pattern (FWHM) at pointing position, (θ_0,ϕ_0)

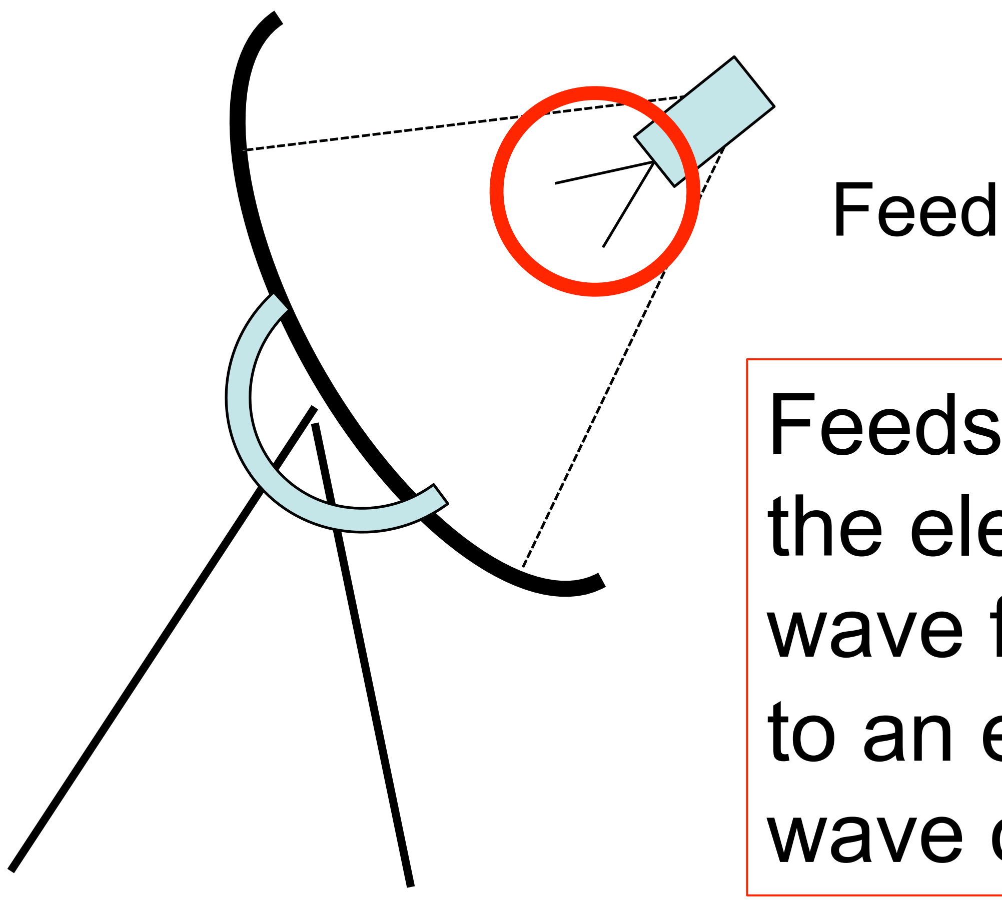
$B(\theta,\phi)$ Brightness distribution of source

$S_0(\theta_0,\phi_0)$ Measured flux density at pointing position, (θ_0,ϕ_0)

$$S_0(\theta_0,\phi_0) = \int B(\theta,\phi) P_n(\theta-\theta_0,\phi-\phi_0)\, d\phi d\phi$$

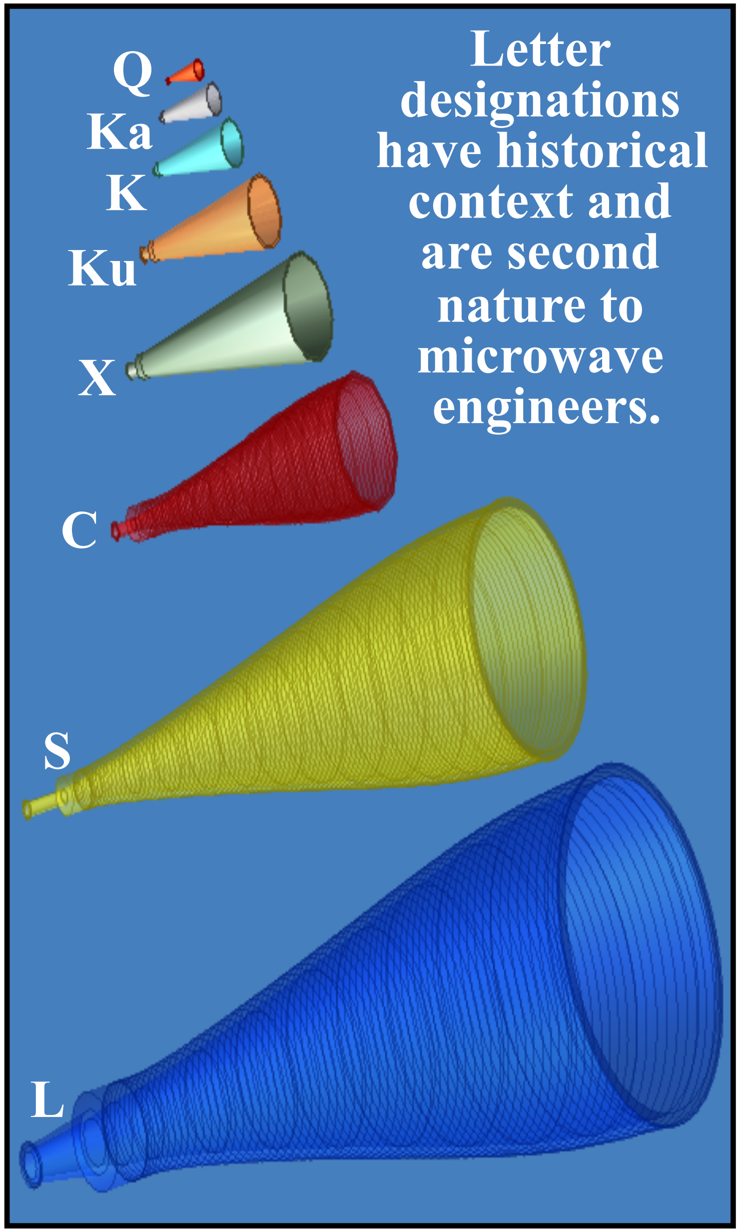
$$S_0 = B * P_n$$

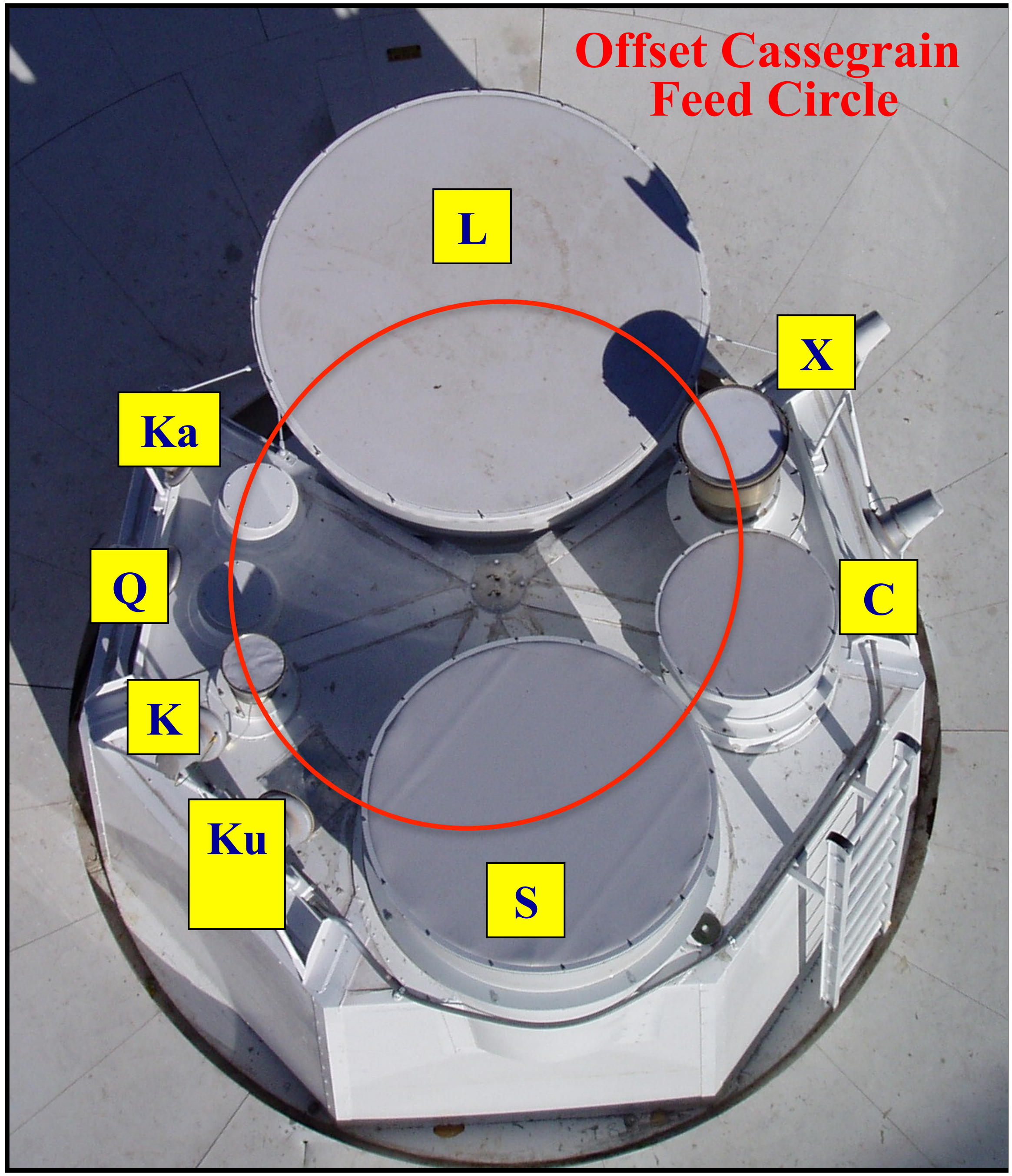
Feeds



Feeds translate the electromagnetic wave from "vacuum" to an electromagnetic wave on a conductor

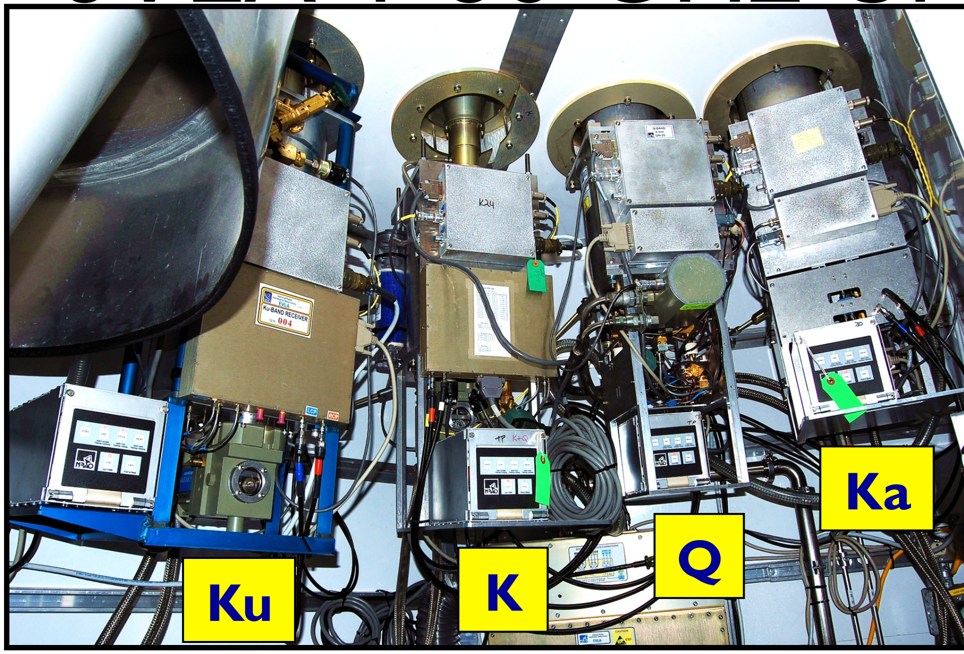
JVLA Feeds





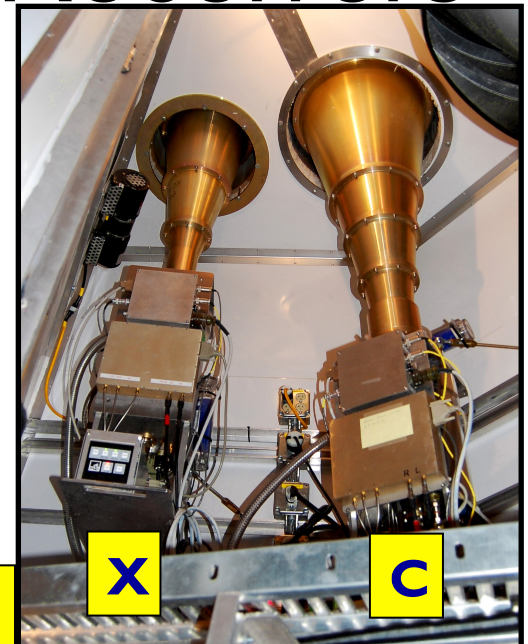
Jim Ruff's Web Pages - http://www.aoc.nrao.edu/~jruff/A1Vertex.jpg

JVLA 1-50 GHz Cryogenic Receivers



Upper Level

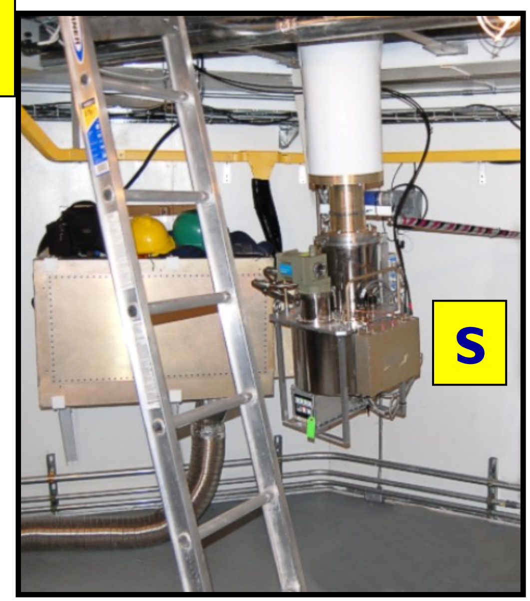
C = 4 - 8 GHz
X = 8-12 GHz
Ku = 12-18 GHz
K = 18-26 GHz
Ka = 26-40 GHz
Q = 40-50 GHz



Vertex Cabin

Lower Level

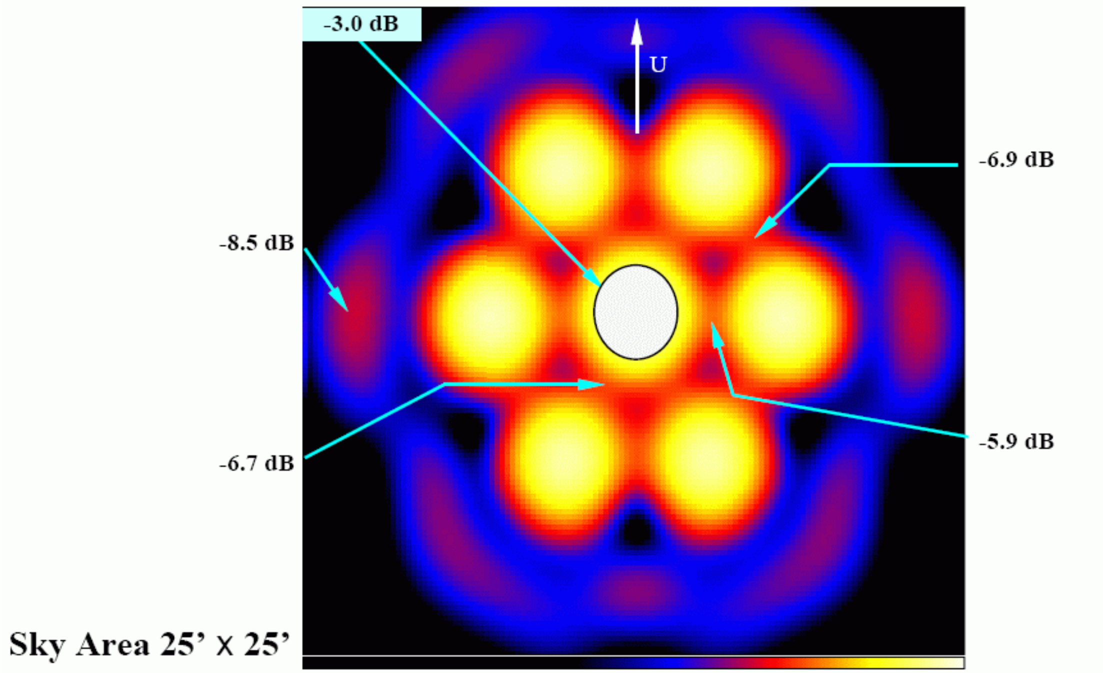
L = 1-2 GHz
S = 2-4 GHz



Multi-beam feed arrays

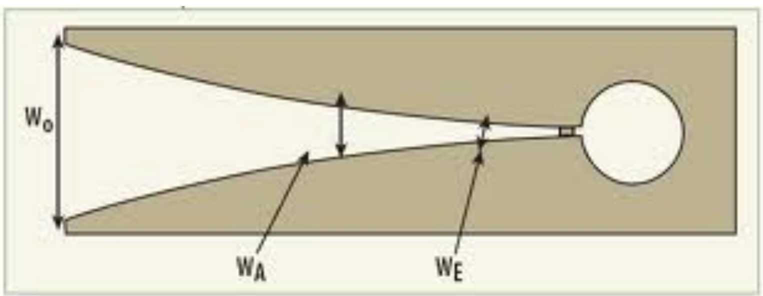
Distinct receivers each with its own feed horn: multiple feed-receiver systems

Parkes

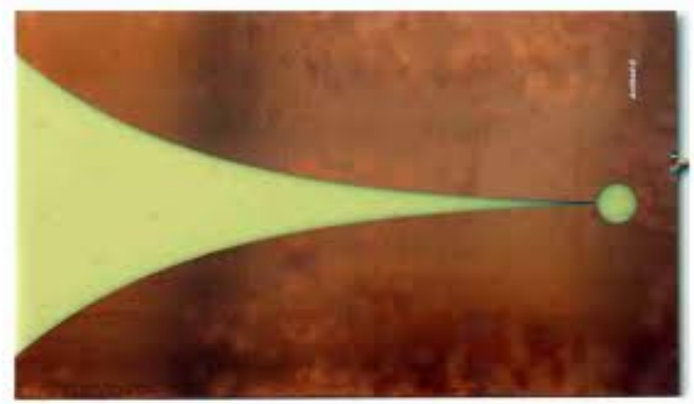


Arecibo

Phased array feeds



1. The design of a Vivaldi antenna (from ref. 8) involves setting the input slot width ($_W$), the slot width at the radiating area (W_A), and the output slot width (W_o).



144-element Vivaldi array designed and assembled at UMass.

Westerbork
APERTIV (Aperture Tile in Focus)

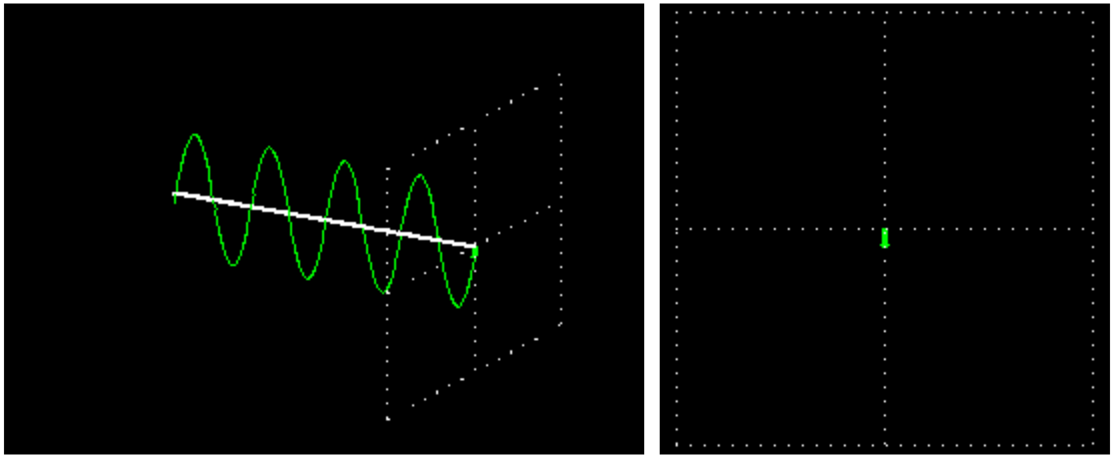
Receivers do not act independently
They are sensitive to the EM field
across the array

Widely used in medical ultra sound applications

Primer - Linearly Polarized Signals

Vertical

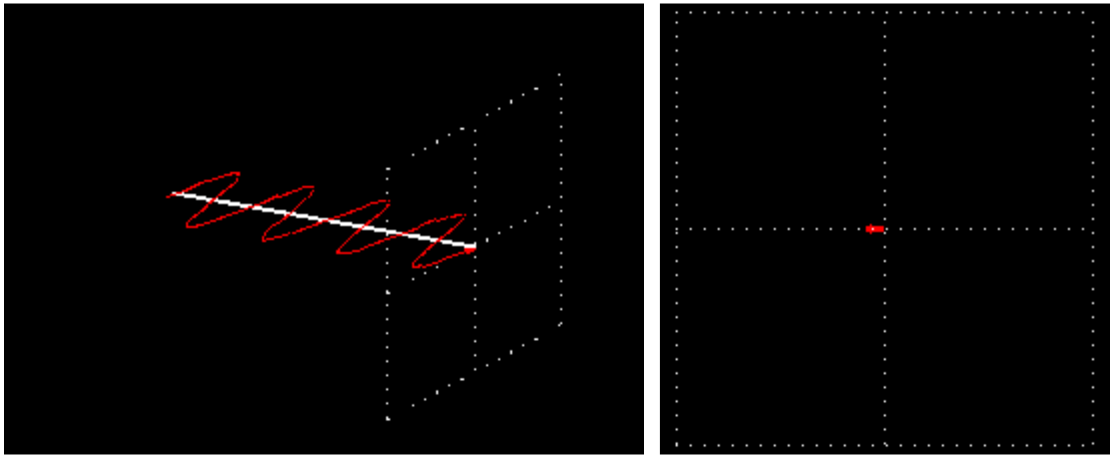
$$E_y = A\sin(x/\lambda - \omega t)$$



A device called an Orthomode Transducer is needed to separate both linear polarizations simultaneously.

Horizontal

$$E_z = A\sin(x/\lambda - \omega t)$$



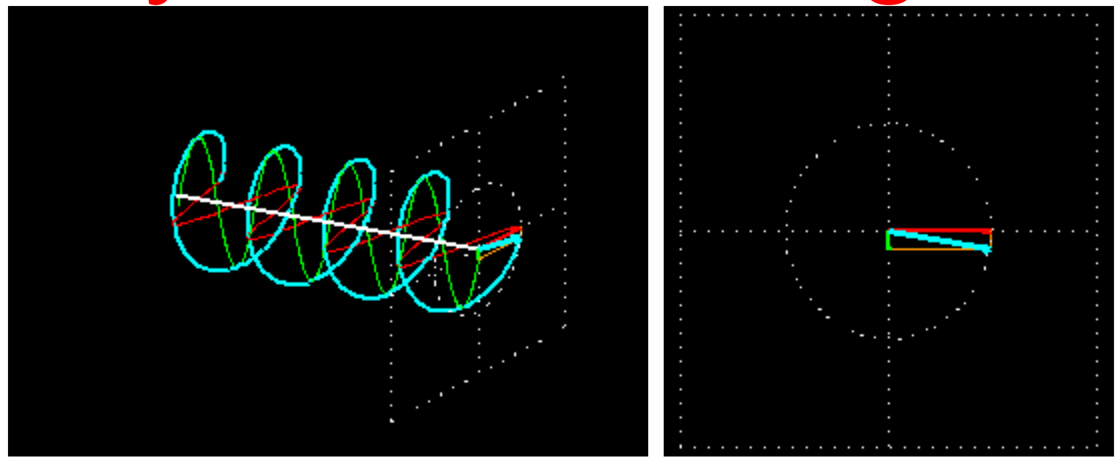
***Interactive animations of electromagneticwaves*, András Szilágyi, Institute of Enzymology, Hungarian Academy of Sciences**
http://titan.physx.u-szeged.hu/~mptl11/Proceedings/InteractiveAnimationsOfElectromagneticWaves.ppt

Primer - Circularly Polarized Signals

Left Circular

$$E_y = A\sin(x/\lambda - \omega t + 90°)$$

$$E_z = A\sin(x/\lambda - \omega t)$$



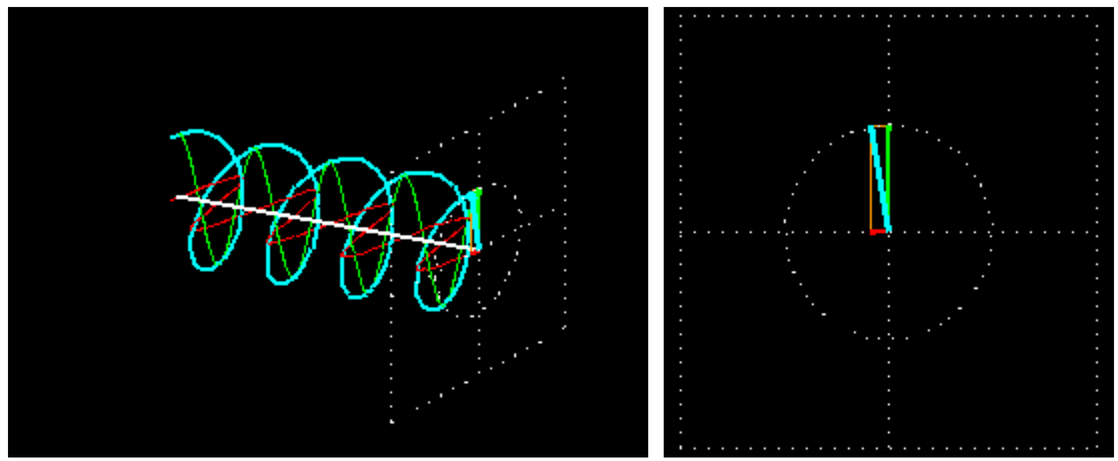
Radio Astronomy Definition

To convert linear to circular, a 90 degree phase-shifter is needed which retards one of the linear polarizations.

Right Circular

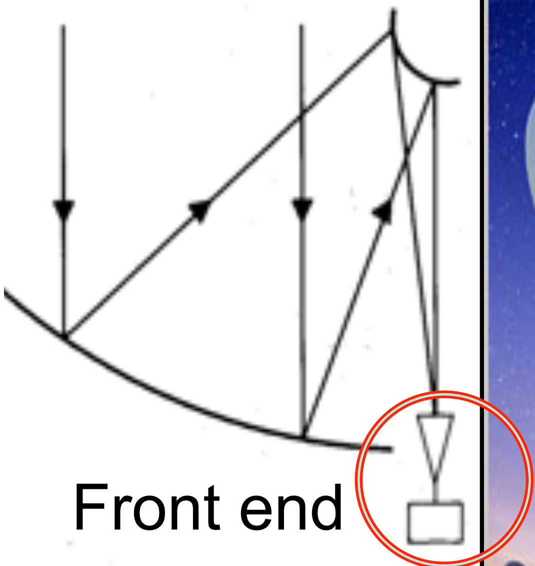
$$E_y = A\sin(x/\lambda - \omega t - 90°)$$

$$E_z = A\sin(x/\lambda - \omega t)$$



***Interactive animations of electromagneticwaves*, András Szilágyi, Institute of Enzymology, Hungarian Academy of Sciences**
http://titan.physx.u-szeged.hu/~mptl11/Proceedings/InteractiveAnimationsOfElectromagneticWaves.ppt

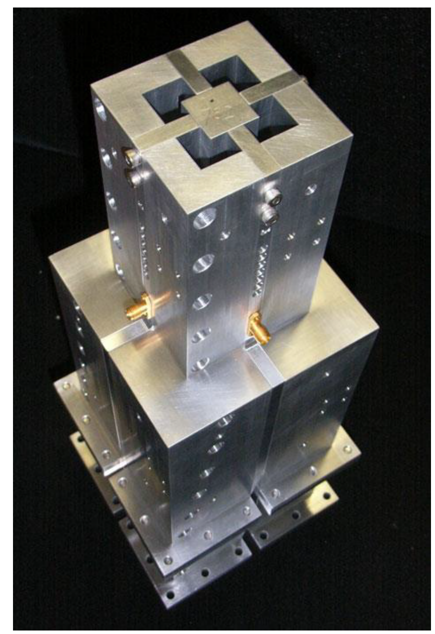
Polarization separation at front end



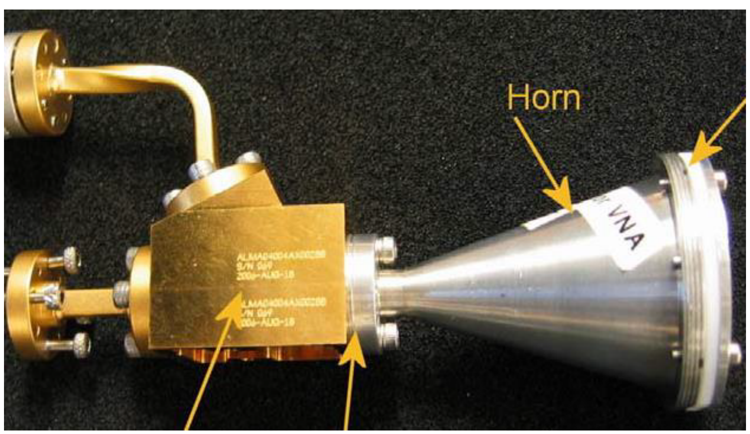
Front end

Dual
Offset
(Meerkat)

EVLA
2-4 GHz

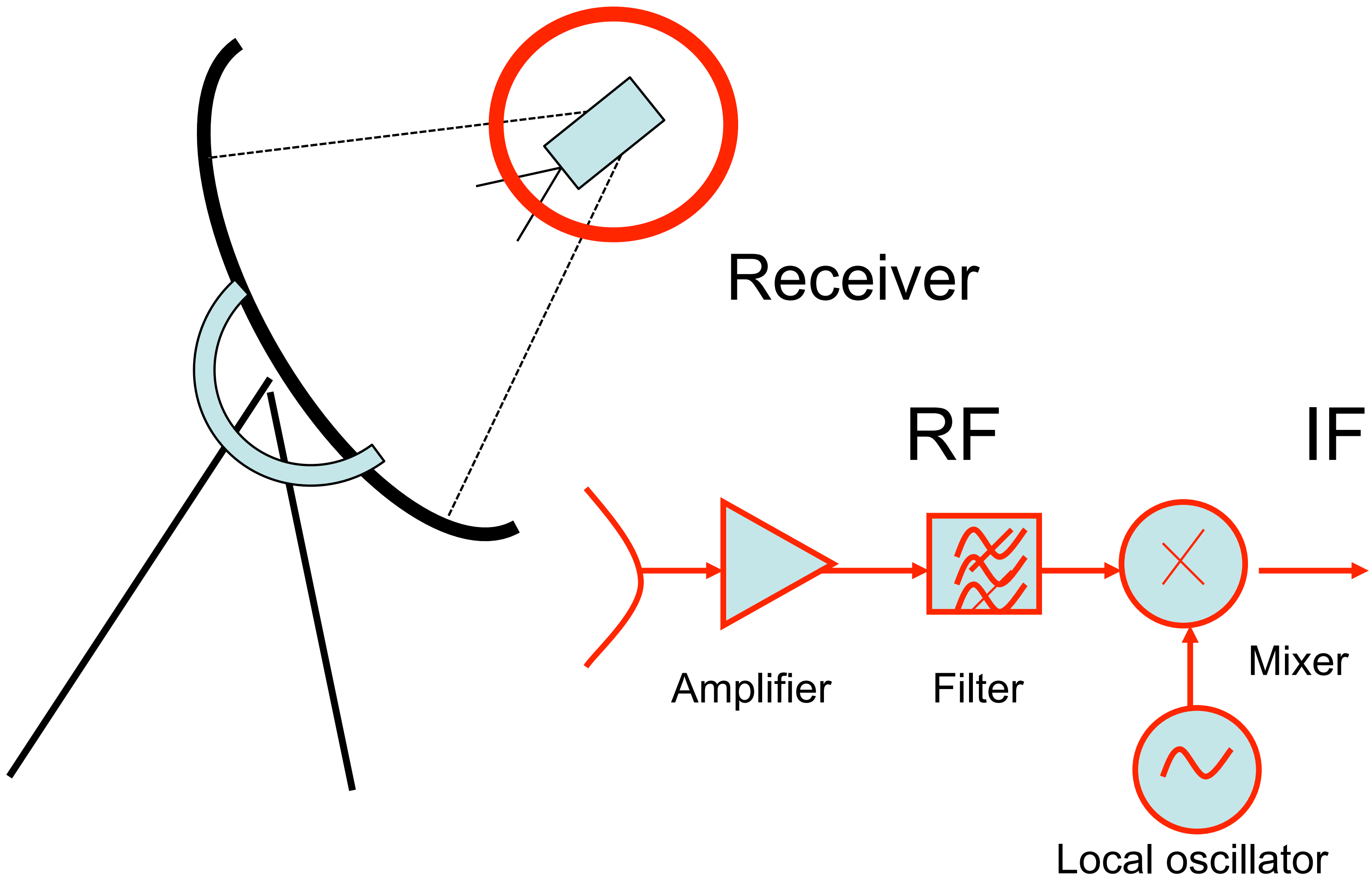


ALMA,
100 GHz



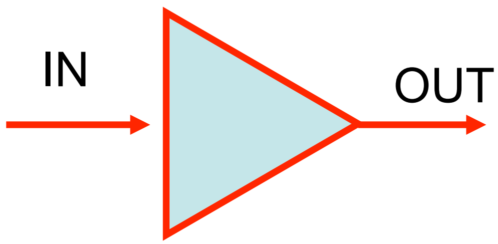
Receiver

1. **Amplifies weak RF (radio frequency) signal**
2. **Filters RF signal**
3. **Mixes RF signal to IF (intermediate frequency) signal on coaxial cable for digitization**



Amplifiers

Amplifiers have two ports, one input and one output
Amplification: 10 to 30 dB
Same frequency for input and output

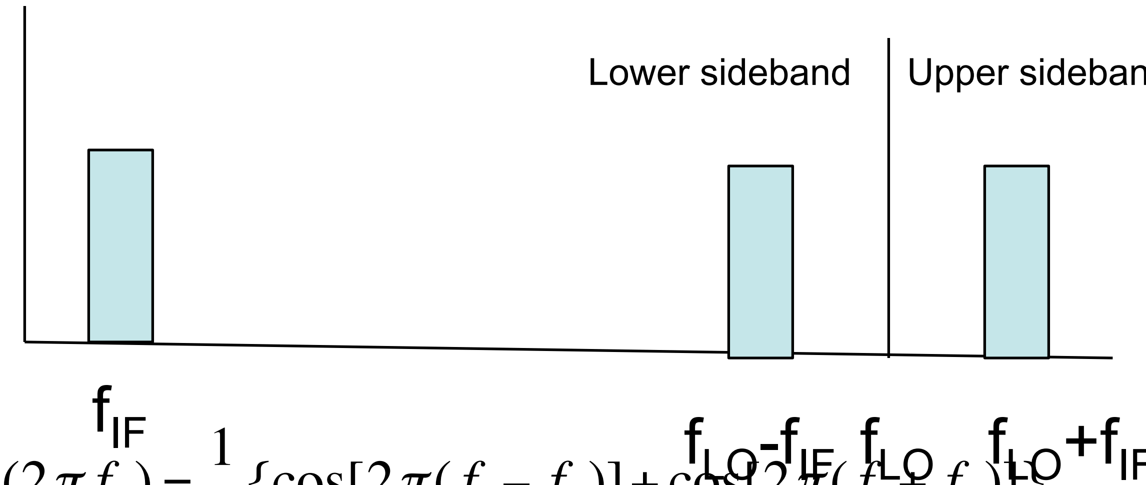


Low noise amplifiers (LNA) often use Field Effect Transistors (FETs)

Mixers and LOs

Mixers have two input ports (RF and LO) and one output port (IF)
The phase of the RF signal is preserved in the IF signal

Mixer



$$\cos(2\pi f_1)\cos(2\pi f_2) = \frac{1}{2}\{\cos[2\pi(f_1 - f_2)] + \cos[2\pi(f_1 + f_2)]\}$$

$$\cos(2\pi(f_{LO} - f_{IF}))\cos(2\pi f_{LO}) = \frac{1}{2}\{\cos[2\pi(f_{IF})] + \cos[2\pi(2f_{LO} - f_{IF}$$

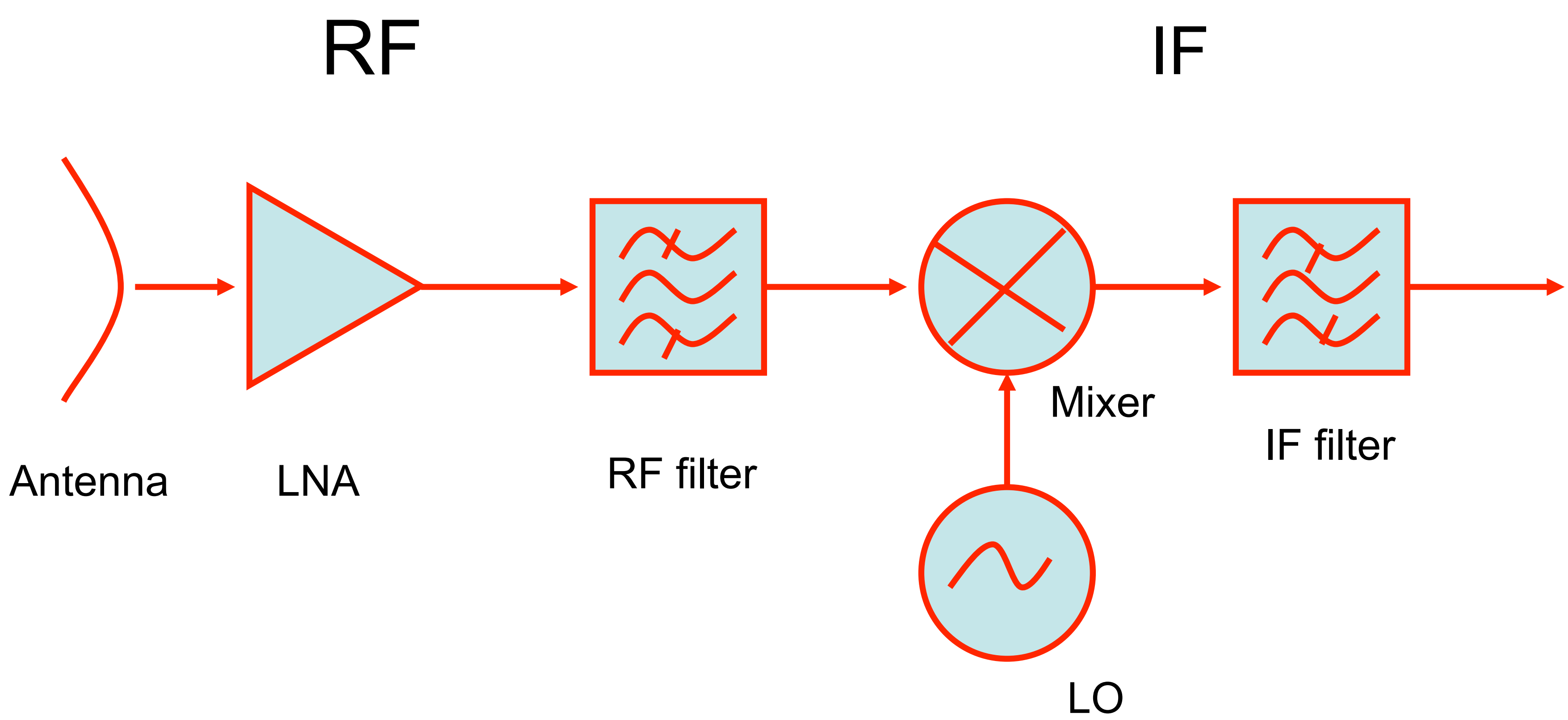
Example:

$$\cos(2\pi(f_{LO} - f_{IF}))\cos(2\pi f_{LO}) = \frac{1}{2}\{\cos[2\pi(f_{IF})] + \cos[2\pi(2f_{LO} - f_{IF})]\}$$

LO: Local oscillator

Receivers

Most, if not all, receivers in radio astronomy are superheterodyne receivers

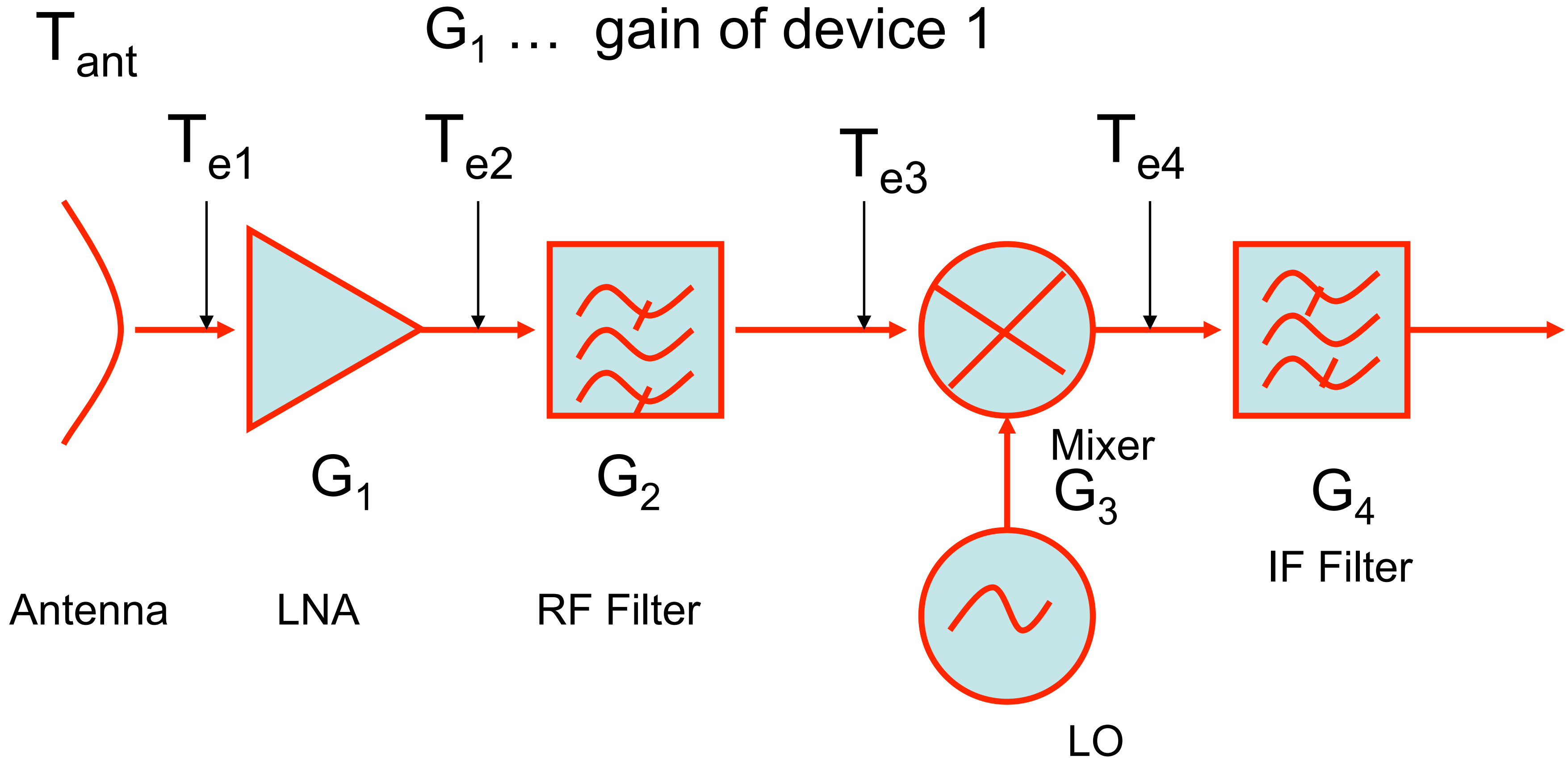


System temperature of receiver

$$T_{sys} = T_{ant} + T_{e1} + T_{e2}/G1 + T_{e3}/(G_1G_2) + T_{e4}/(G_1G_2G_3)$$

T_{e1} … equivalent input temperature of device 1

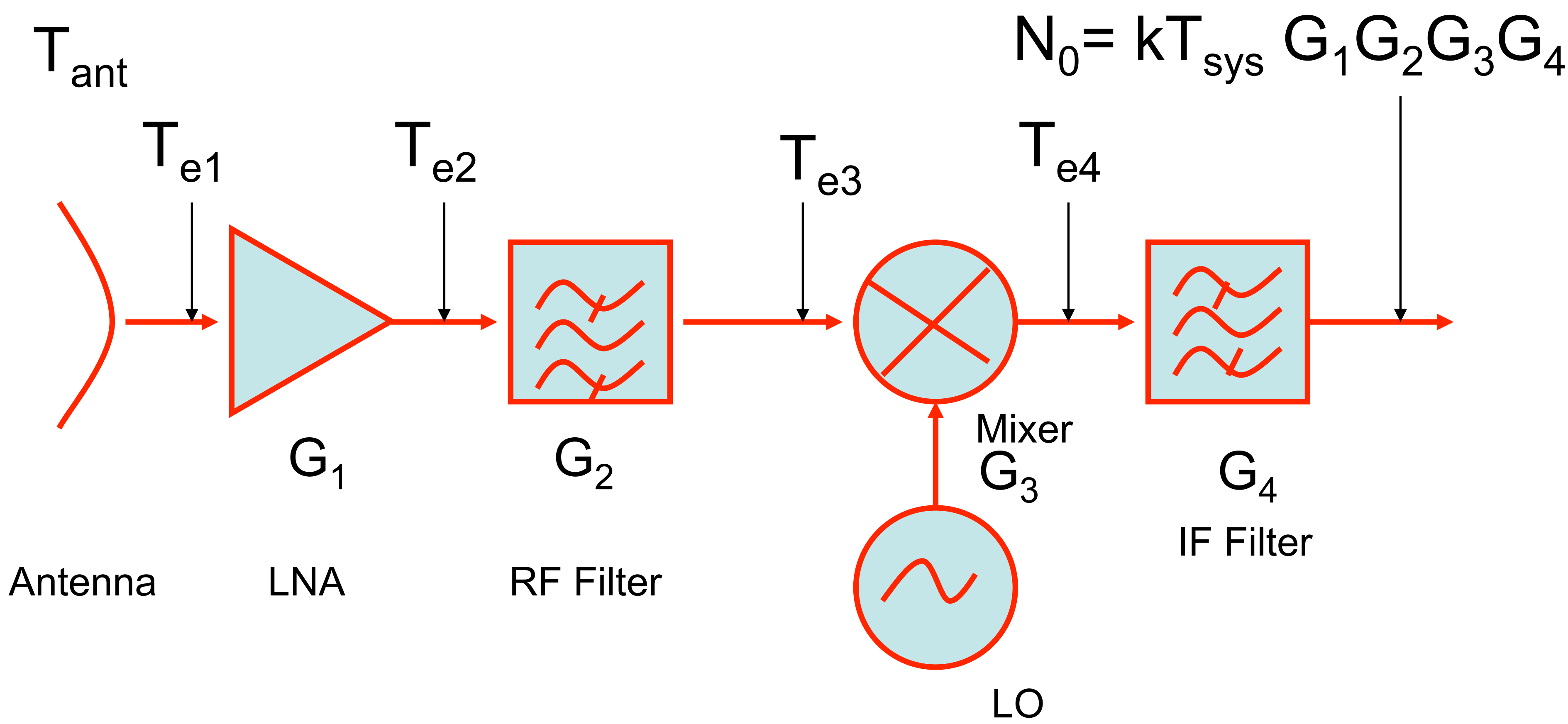
G_1 … gain of device 1



System temperature of receiver

$$T_{sys} = T_{ant} + T_{e1} + T_{e2}/G1 + T_{e3}/(G_1G_2) + T_{e4}/(G_1G_2G_3)$$

N_0: noise spectral density (W/Hz)

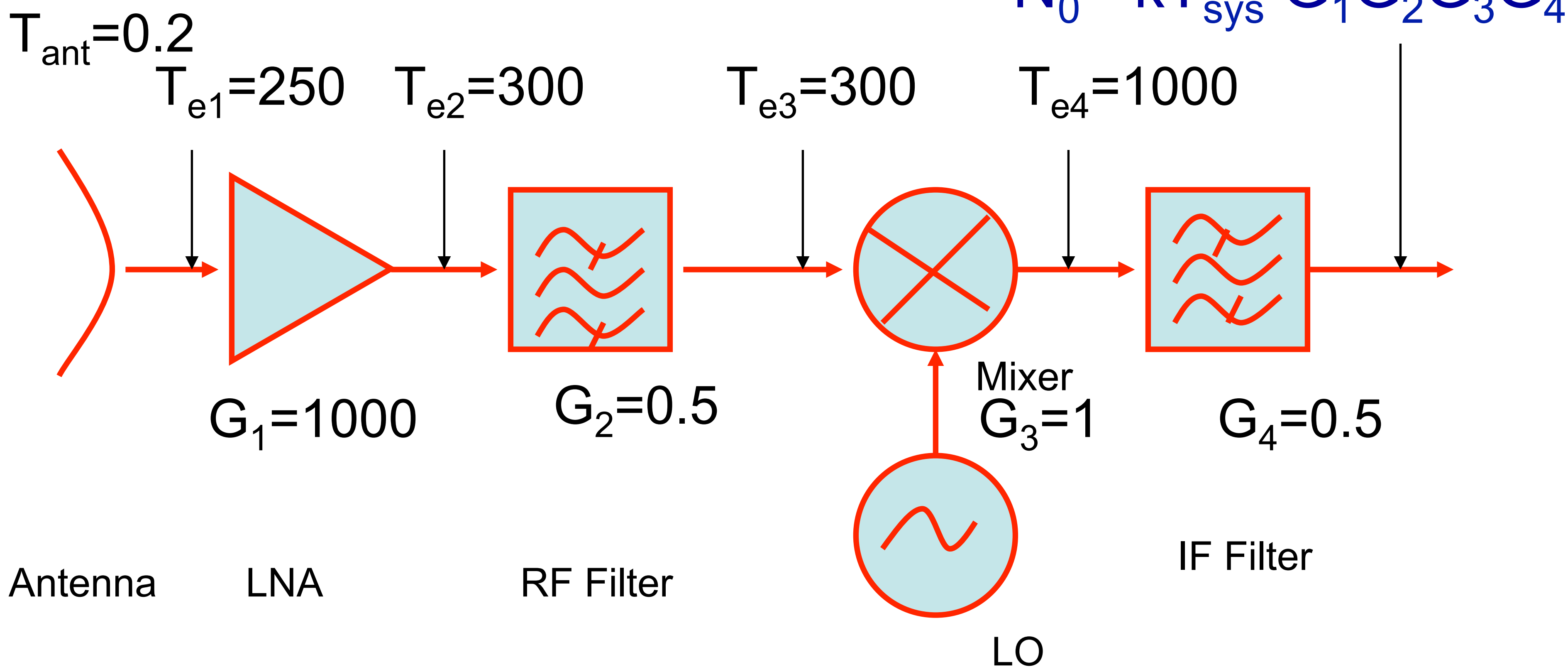


System temperature of receiver

$$T_{sys} = T_{ant} + T_{e1} + T_{e2}/G1 + T_{e3}/(G_1G_2)+T_{e4}/(G_1G_2G_3)$$

N_0: noise spectral density (W/Hz)

$$N_0 = kT_{sys}\ G_1G_2G_3G_4$$



$$T_{sys} = T_{ant} + T_{e1} + T_{e2}/G1 + T_{e3}/(G_1G_2) + T_{e4}/(G_1G_2G_3)$$

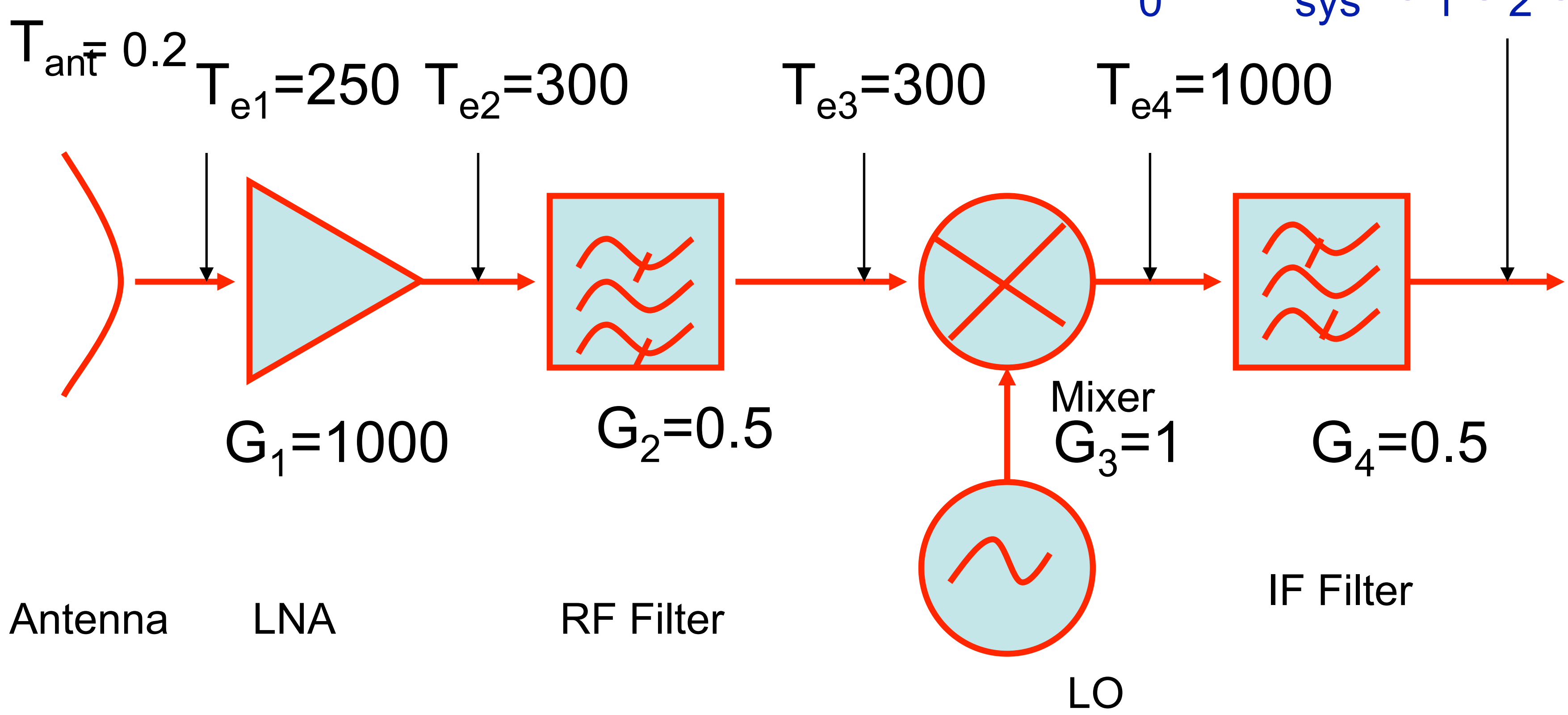
$$= 0.2 + 250 + 300/1000 + 300/500 + 1000/500$$

$$= \mathbf{253\ K}$$

$$N_0 = 1.38 \times 10^{-23} \times 253 \times 1000 \times 0.5 \times 1 \times 0.5$$

$$= \mathbf{8.7 \times 10^{-18}\ W/Hz}$$

$$N_0 = kT_{sys}\, G_1G_2G_3G_4$$



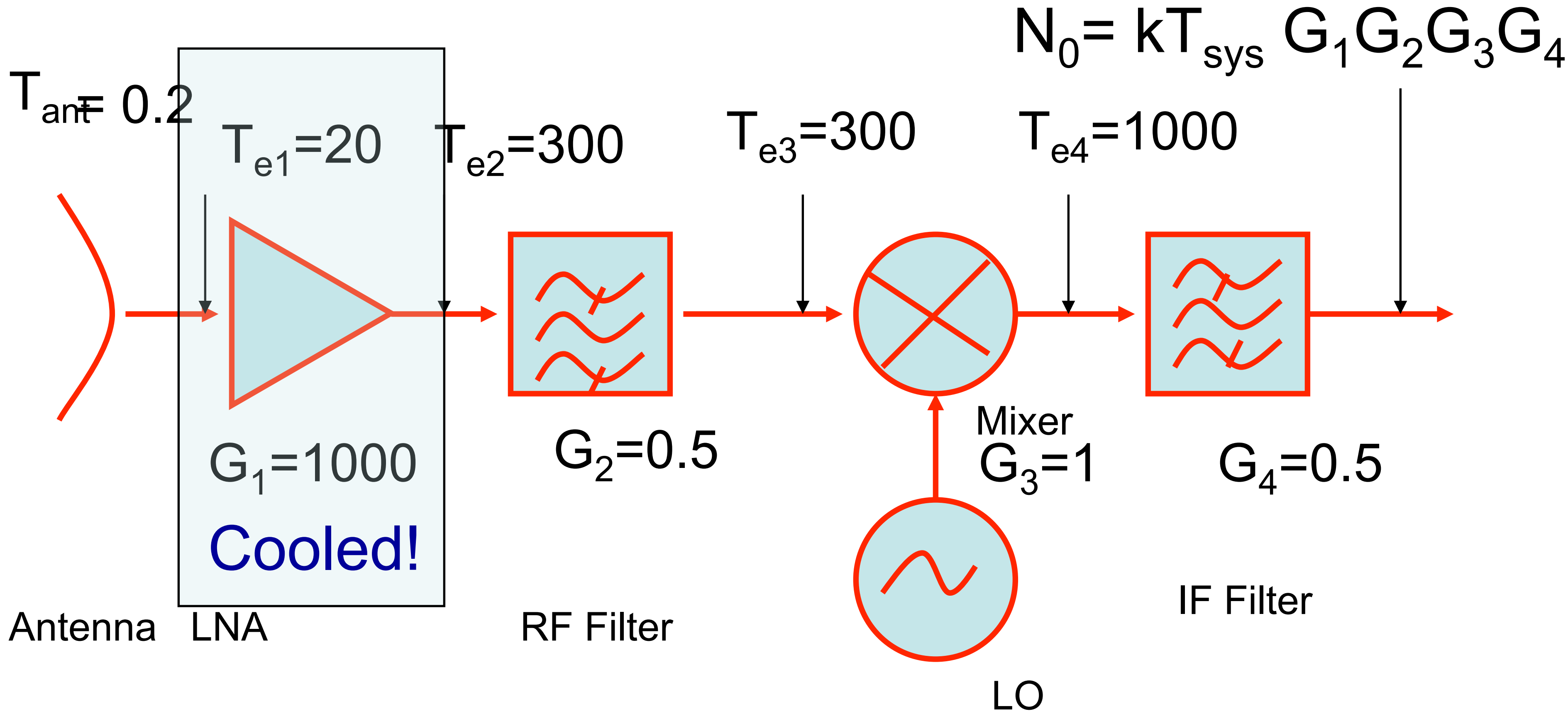
$$T_{sys} = T_{ant} + T_{e1} + T_{e2}/G1 + T_{e3}/(G_1G_2) + T_{e4}/(G_1G_2G_3)$$

$$= 0.2 + 20 + 300/1000 + 300/500 + 1000/500$$

$$= \mathbf{23\ K}$$

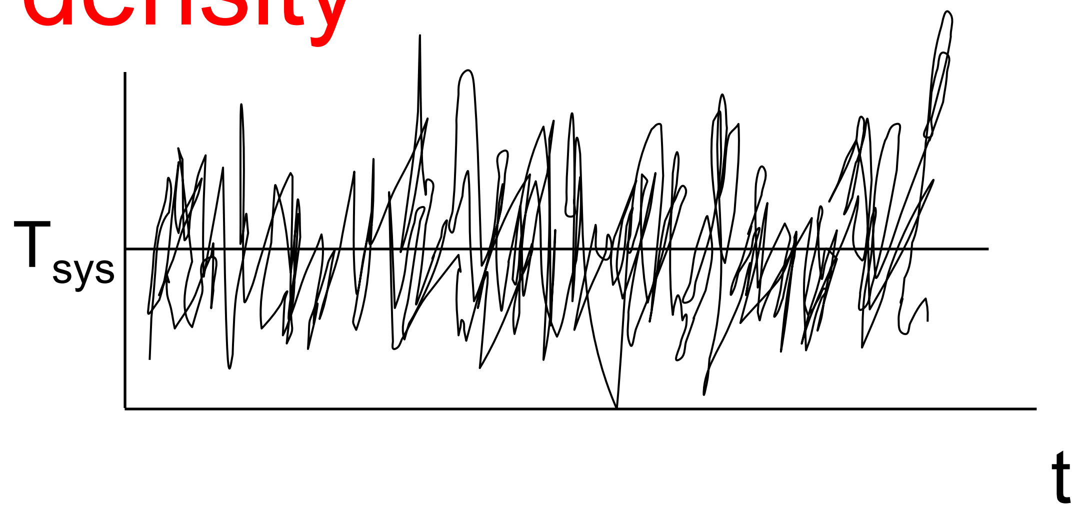
$$N_0 = 1.38 \times 10^{-23} \times 23 \times 1000 \times 0.5 \times 1 \times 0.5$$

$$= \mathbf{7.9 \times 10^{-19}\ W/Hz}$$



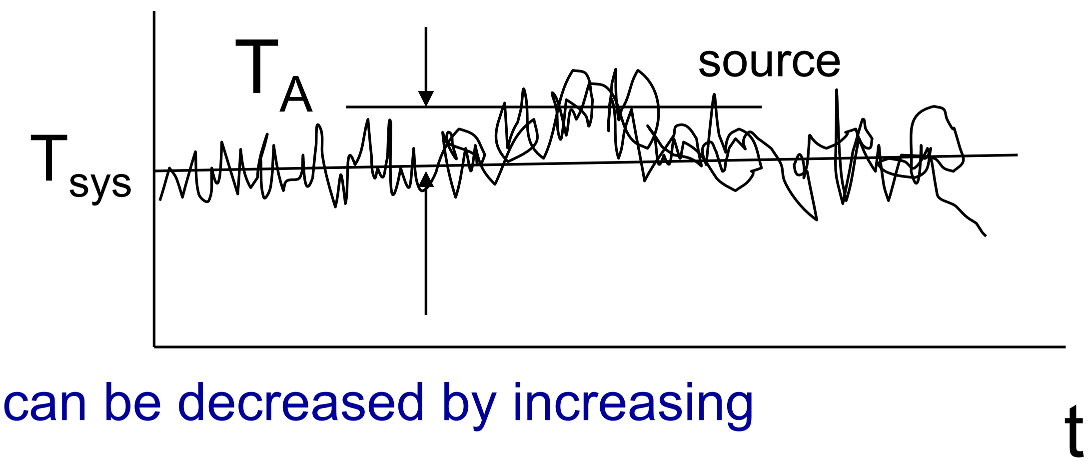
The minimum detectable flux density

$$T_{sys} = T_A + T_R$$



$$\Delta T_{\min} = \frac{T_{sys}}{\sqrt{\Delta t \Delta \nu}}$$

$$\Delta S_{\min} = \frac{2k}{A_{eff}} \frac{T_{sys}}{\sqrt{\Delta t \Delta \nu}}$$



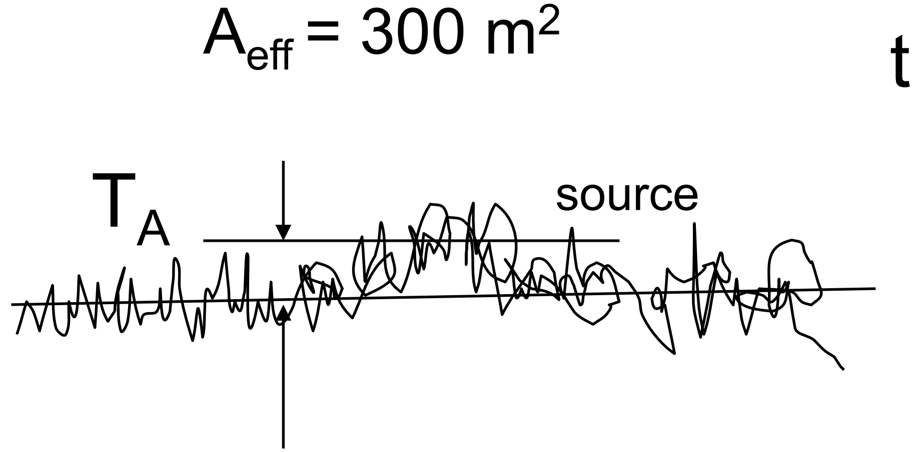
- Rms of Tsys fluctuations can be decreased by increasing Δt and/or Δv.
- Scanning the antenna across the source causes increase in T_{sys} due to T_A

Example

$$\Delta T_{\min} = \frac{T_{sys}}{\sqrt{\Delta t \Delta \nu}}$$

$$\Delta S_{\min} = \frac{2k}{A_{eff}} \frac{T_{sys}}{\sqrt{\Delta t \Delta \nu}}$$

T_{sys} = 25 K
Δt = 1s
$\Delta \nu$ = 100 MHz
k = $1.38 \bullet 10^{-23}$ J/K
A_{eff} = 300 m^2



ΔT_{min} = 0.0025 K
ΔS_{min} = $2.3 \bullet 10^{-28}$ W m^{-2} Hz^{-1}
= 0.023 mJy

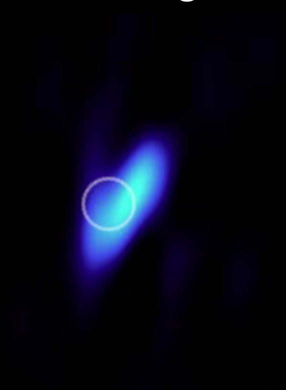
Conclusions

- Nobel prizes are won in radio astronomy
- Different antenna types for different research applications
- Understanding antennas and receivers is crucial for in-depth data analysis

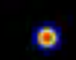
With antenna arrays and sensitive receivers → not only beautiful images of celestial objects…..

…. but also movies of stars when they live and of stars when they die…

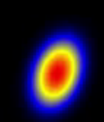
IM Peg



SN 1993J



SN 1986J



Free download: www.yorku.ca/bartel