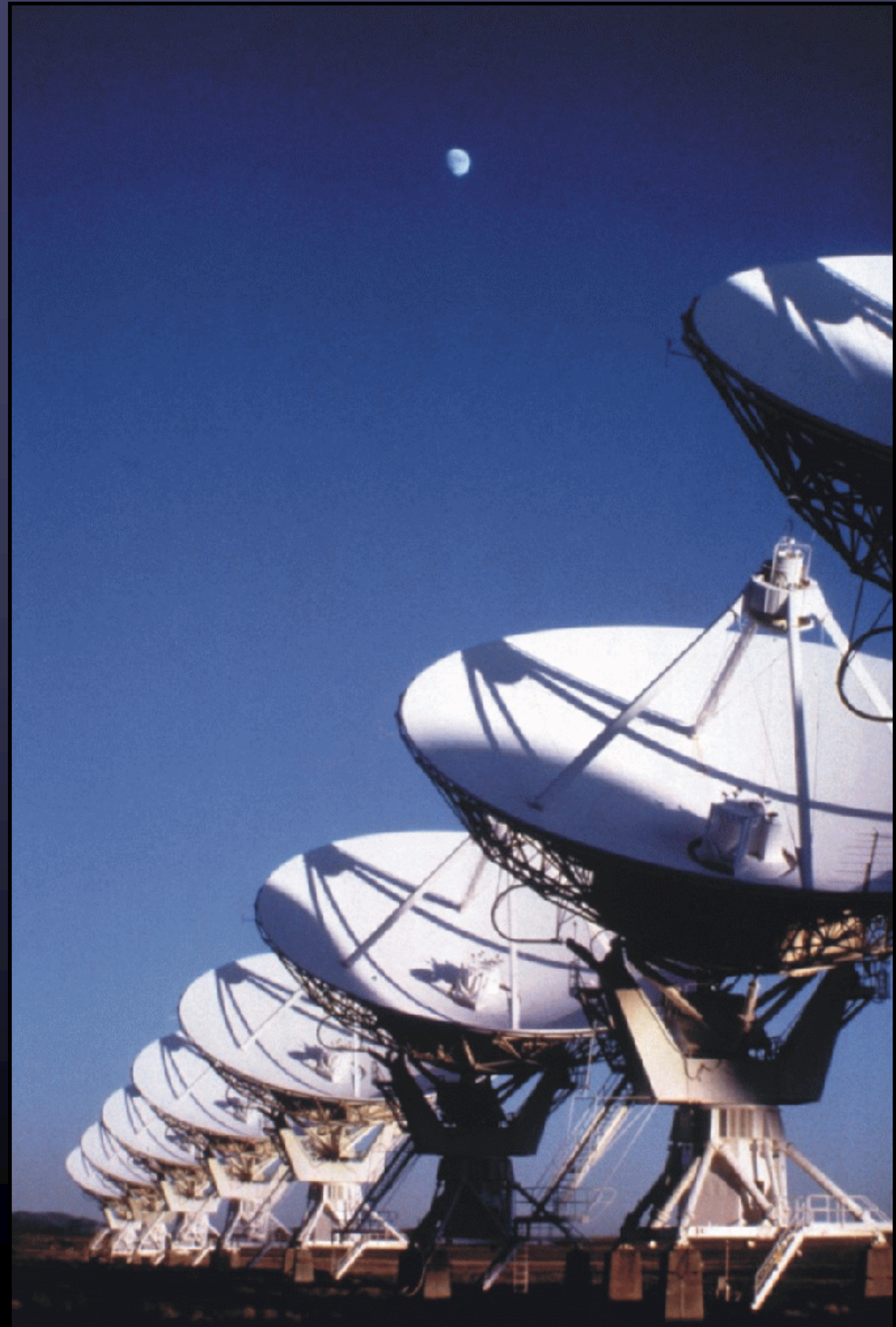
Antennas

Greg Taylor

University of New Mexico



Astronomy 423 at UNM

Radio Astronomy

Outline

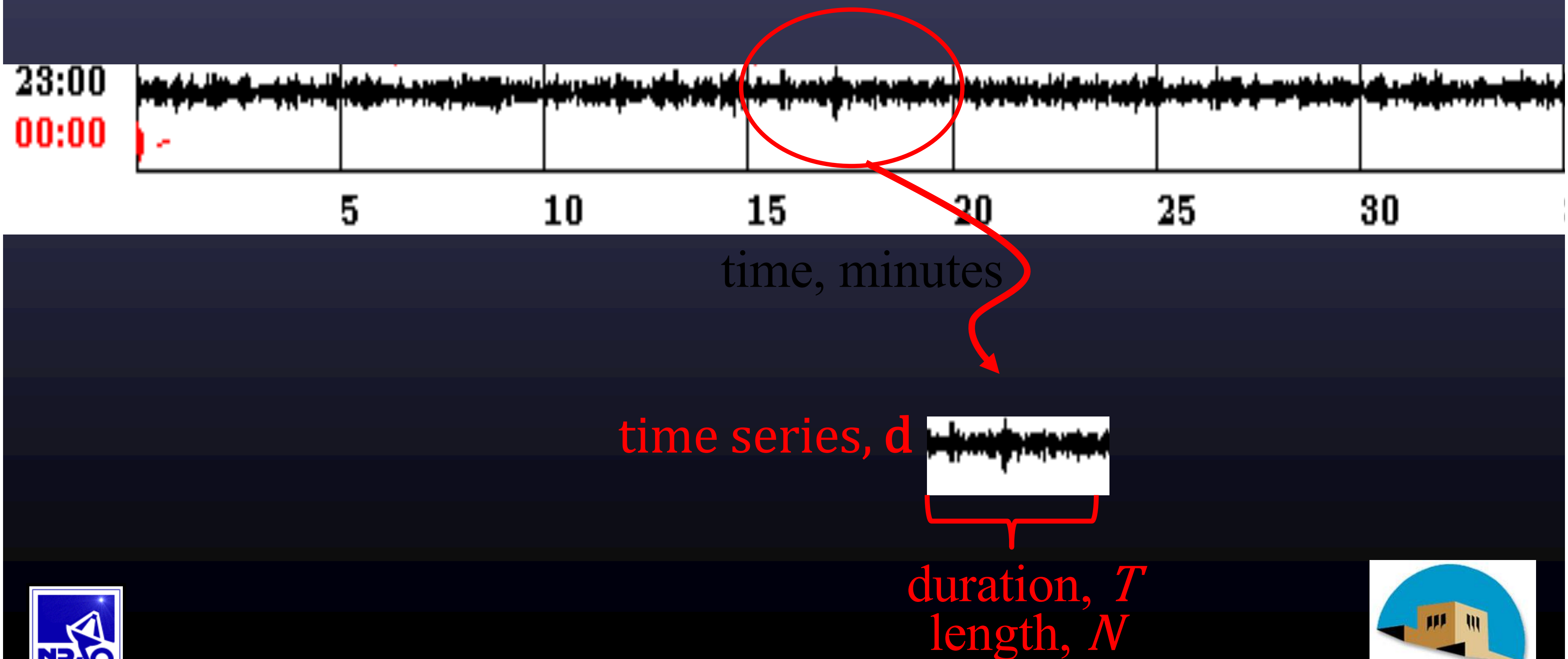
- Fourier Transforms
- Interferometer block diagram
- Antenna fundamentals
- Types of antennas
- Antenna performance parameters
- Receivers
- Dipole Antennas

stationary time series

indefinitely long

but

statistical properties don’t vary with time assume that we are dealing with a fragment of an indefinitely long time series



one quantity that might be stationary is …

“Power”

$$P = \frac{1}{T}\int_{0}^{T}[d(t)]^2\,dt$$

Power

$$P = \frac{1}{T}\int_0^T [d(t)]^2\, dt \approx \frac{\Delta t}{N\Delta t}\sum_{i=1}^{N} [d_i(t)]^2 = \frac{1}{N}\,\mathbf{d}^T\mathbf{d}$$

mean-squared amplitude of time series

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How is power related to power spectral density ?

write Fourier Series as

$\mathbf{d} = \mathbf{G}\mathbf{m}$

were m are the Fourier coefficients

$$P = \frac{1}{N}\mathbf{d}^T\mathbf{d} = \frac{1}{N}(\mathbf{G}\mathbf{m})^T(\mathbf{G}\mathbf{m}) = \frac{1}{N}\mathbf{m}^T[\mathbf{G}^\mathbf{T}\mathbf{G}\,]\mathbf{m}$$

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$$\mathbf{G}^{\mathrm{T}}\mathbf{G}=(N/2)\mathbf{I}$$

now use

$$P = \frac{1}{N}\frac{\mathrm{N}}{2}\mathbf{m}^T\mathbf{m} = \frac{1}{2}\sum_{i=1}^{\frac{N}{2}+1}(A_i^2 + B_i^2) =$$

$$= \frac{1}{2}\sum_{i=1}^{\frac{N}{2}+1}\frac{4}{N^2}|C_i|^2 = \frac{2}{(\Delta t)^2 N^2 \Delta f}\int_0^{f_{ny}}\left|\tilde{d}(f)\right|^2 df$$

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$$\mathbf{G}^T\mathbf{G} = (N/2)\mathbf{I}$$

now use

$$P = \frac{1}{N}\frac{\mathrm{N}}{2}\mathbf{m}^T\mathbf{m} = \frac{1}{2}\sum_{i=1}^{\frac{N}{2}+1}(A_i^2 + B_i^2) =$$

coefficients of complex exponentials

coefficients of sines and cosines

$$= \frac{1}{2}\sum_{i=1}^{\frac{N}{2}+1}\frac{4}{N^2}|C_i|^2 = \frac{2}{(\Delta t)^2 N^2 \Delta f}\int_0^{f_{ny}} \left|\tilde{d}(f)\right|^2 df$$

equals *2/T*

Fourier Transform

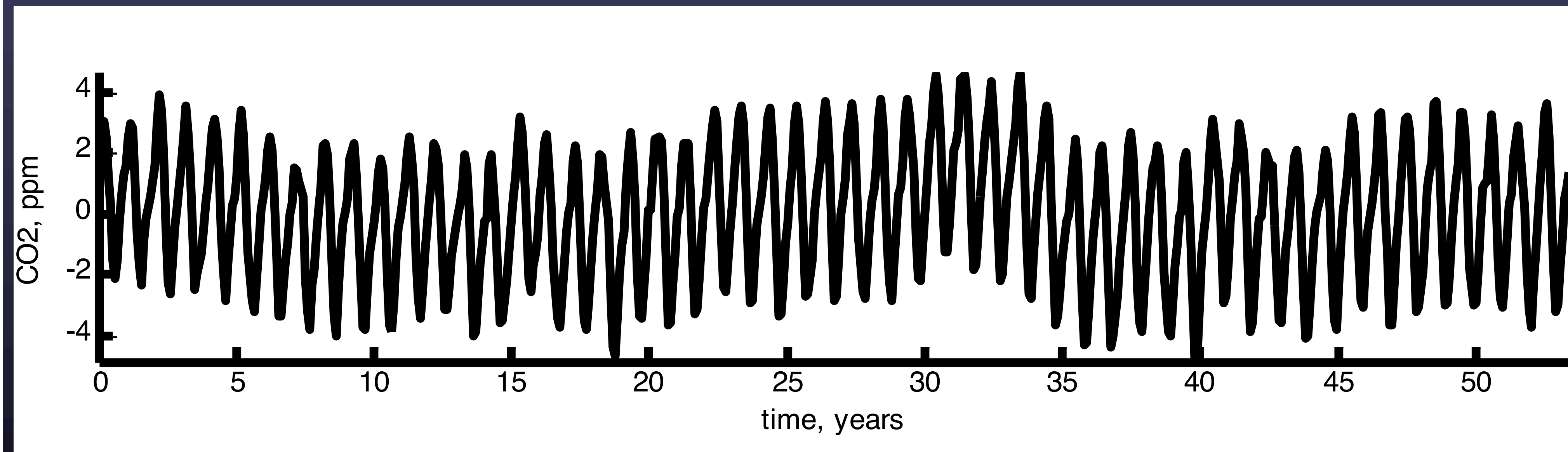
so, if we define the power spectral density of a stationary time series as

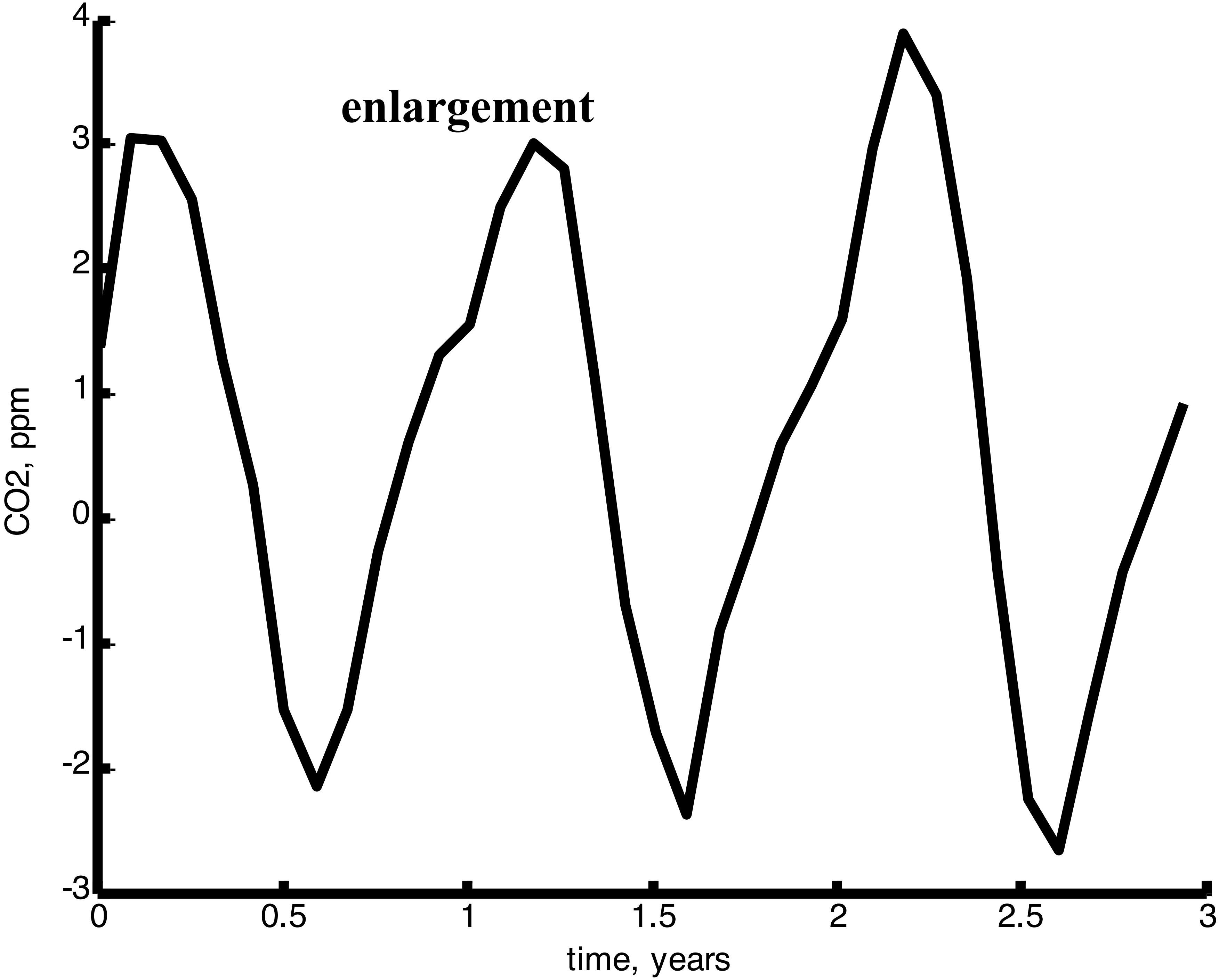
$$s^2(f) = \frac{2}{T}\, \left|\tilde{d}(f)\right|^2$$

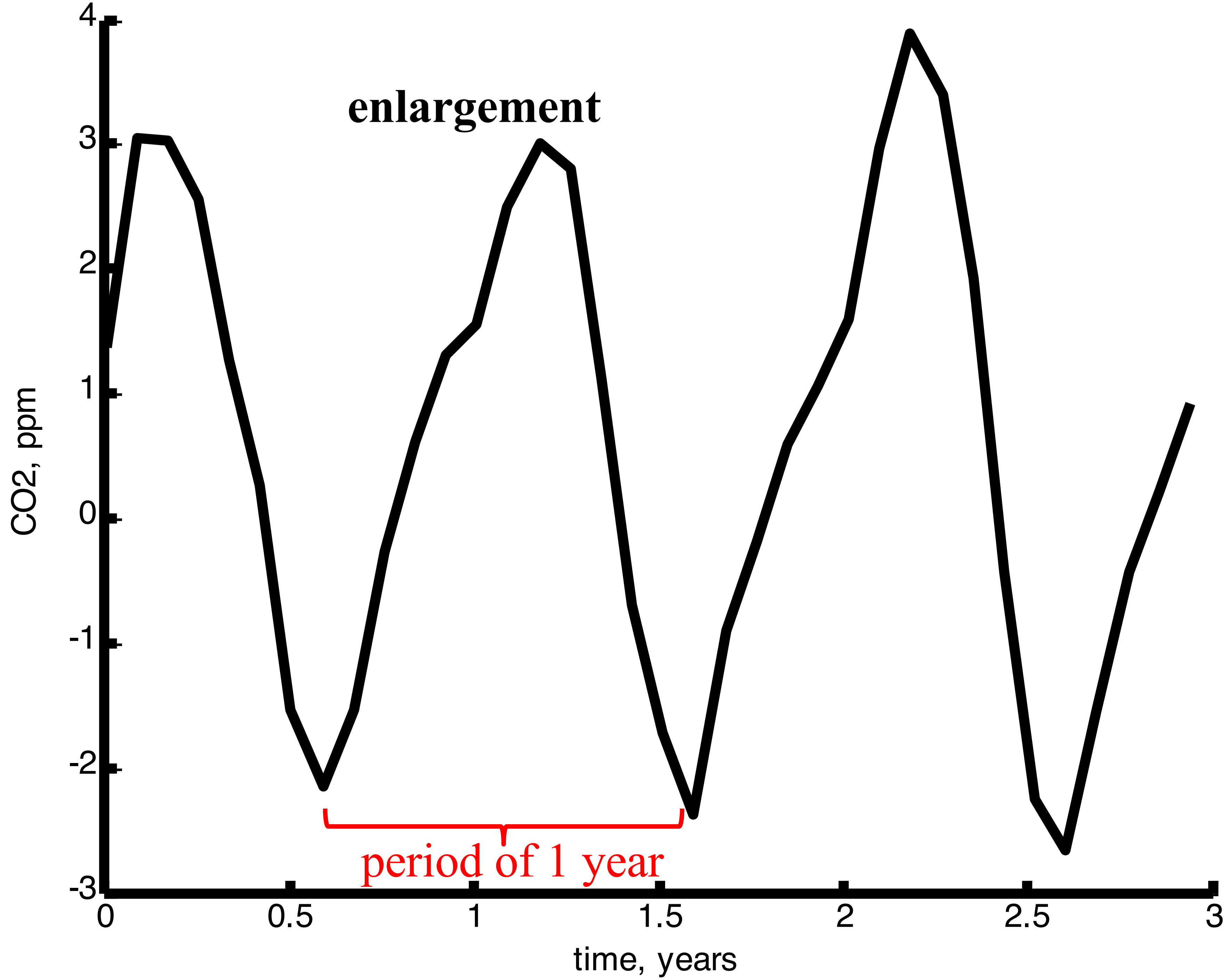
$$\text{then} \quad P = \int_0^{f_{ny}} s^2(f)\,df$$

the integral of the p.s.d. is the power in the time series

Example: Atmospheric CO_2
(after removing anthropogenic trend)

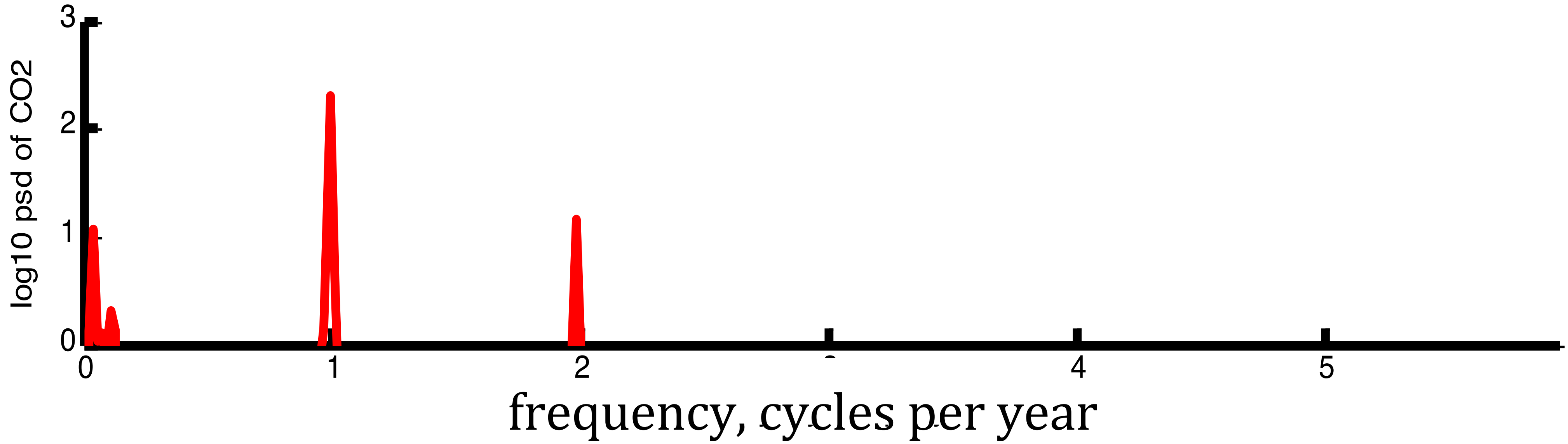



enlargement
CO2, ppm
4
3
2
1
0
-1
-2
-3
0
0.5
1
1.5
2
2.5
3
time, years

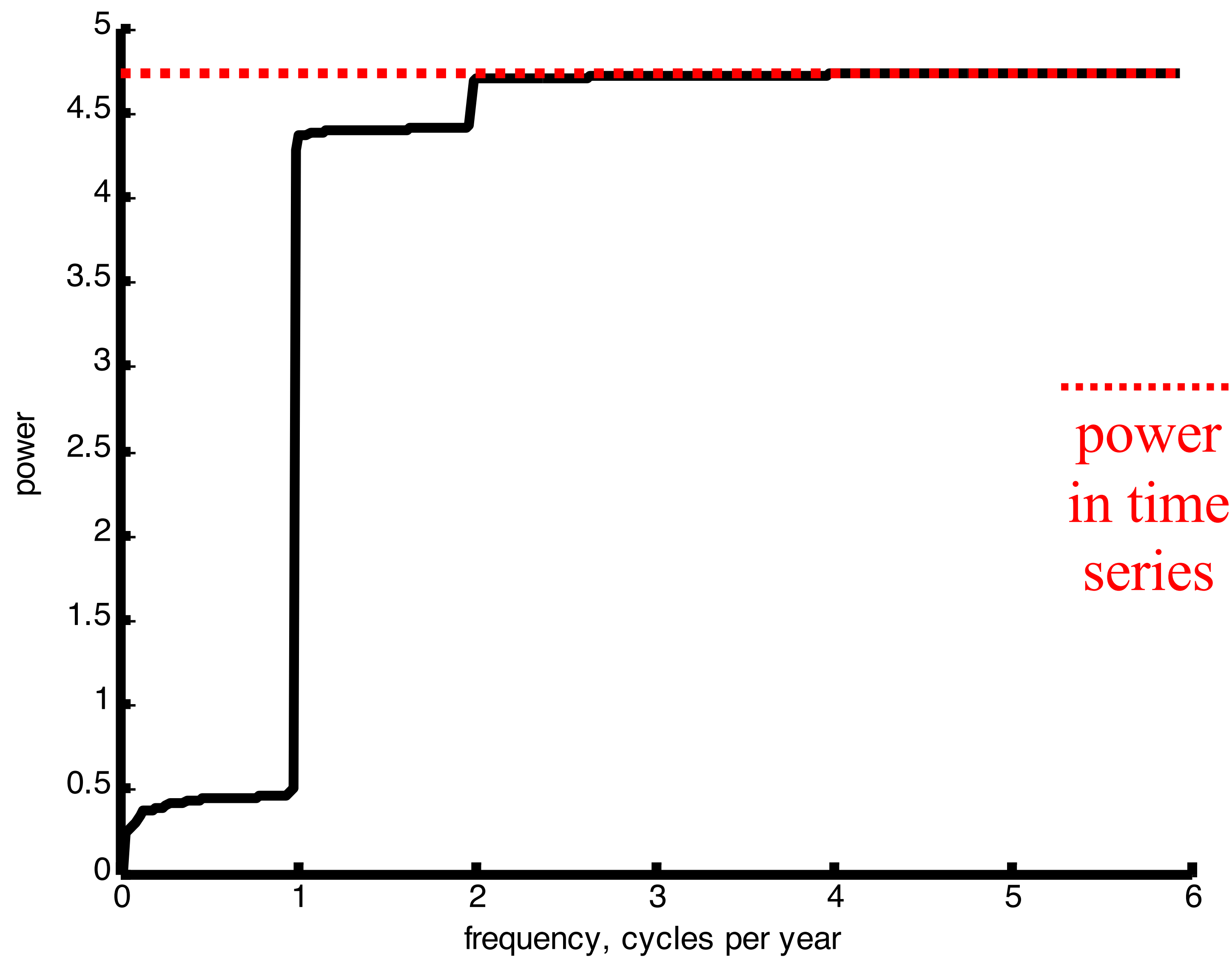


enlargement
period of 1 year
CO2, ppm
time, years
4
3
2
1
0
-1
-2
-3
0
0.5
1
1.5
2
2.5
3

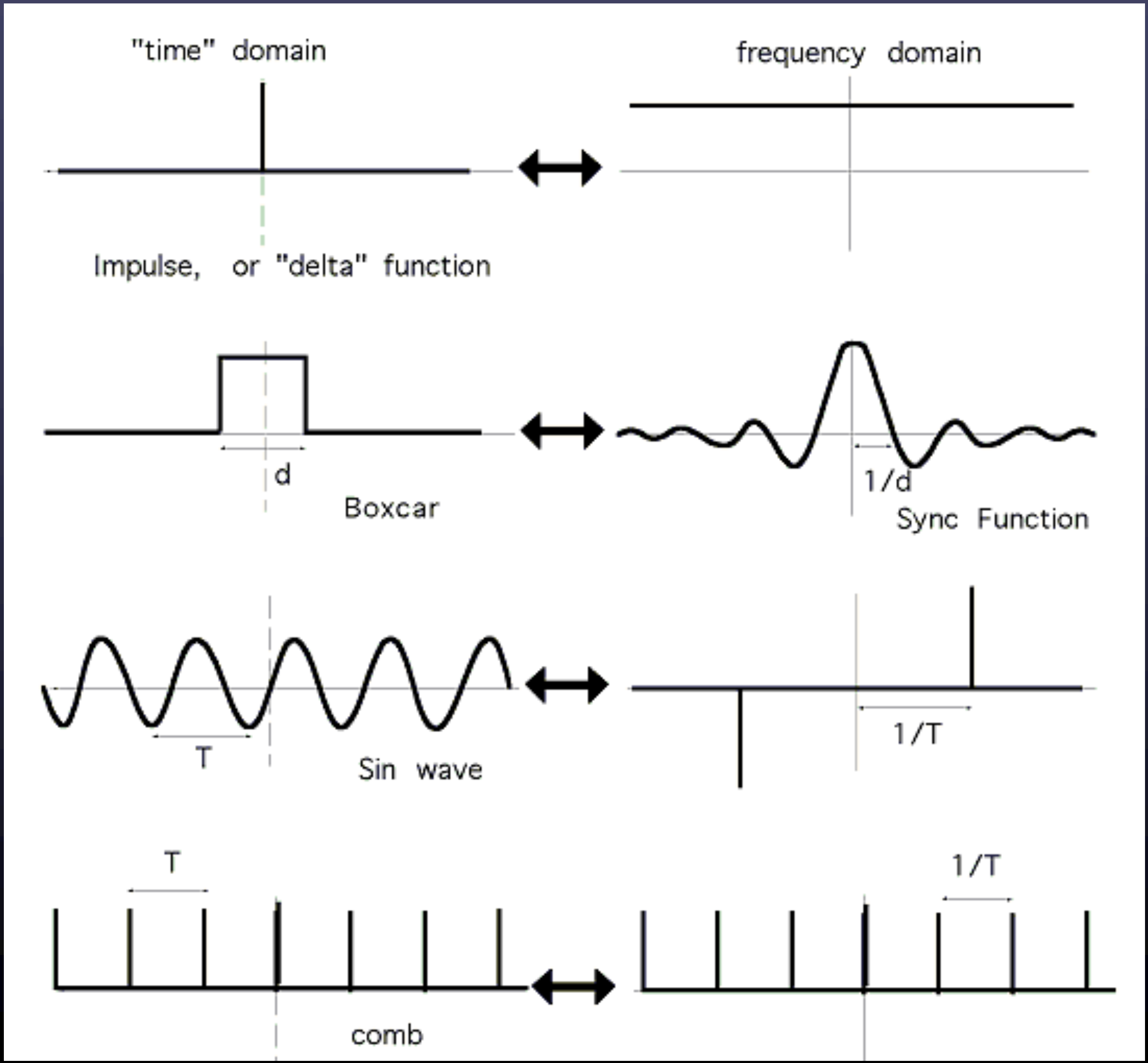
power spectral density



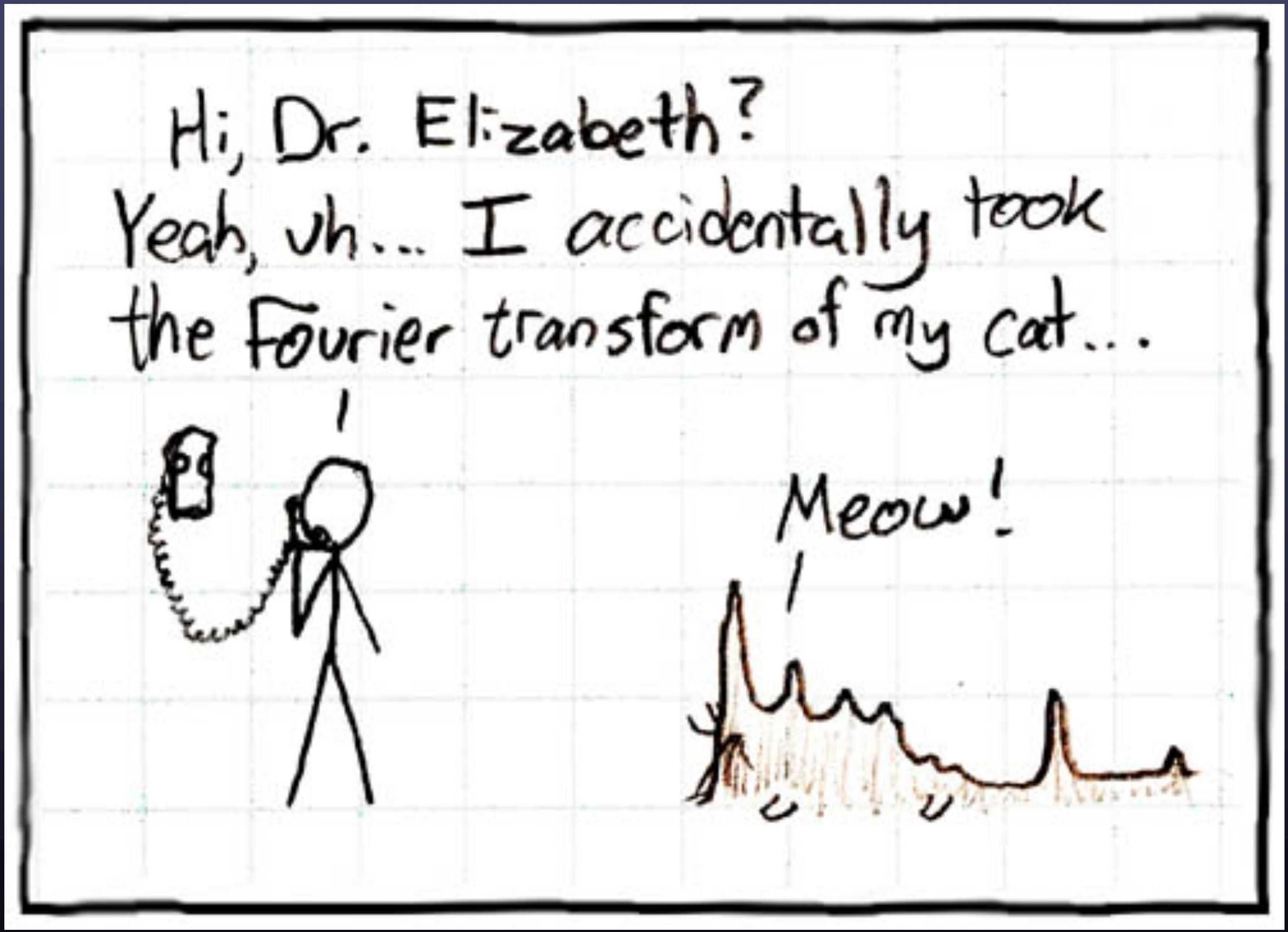
cumulative power

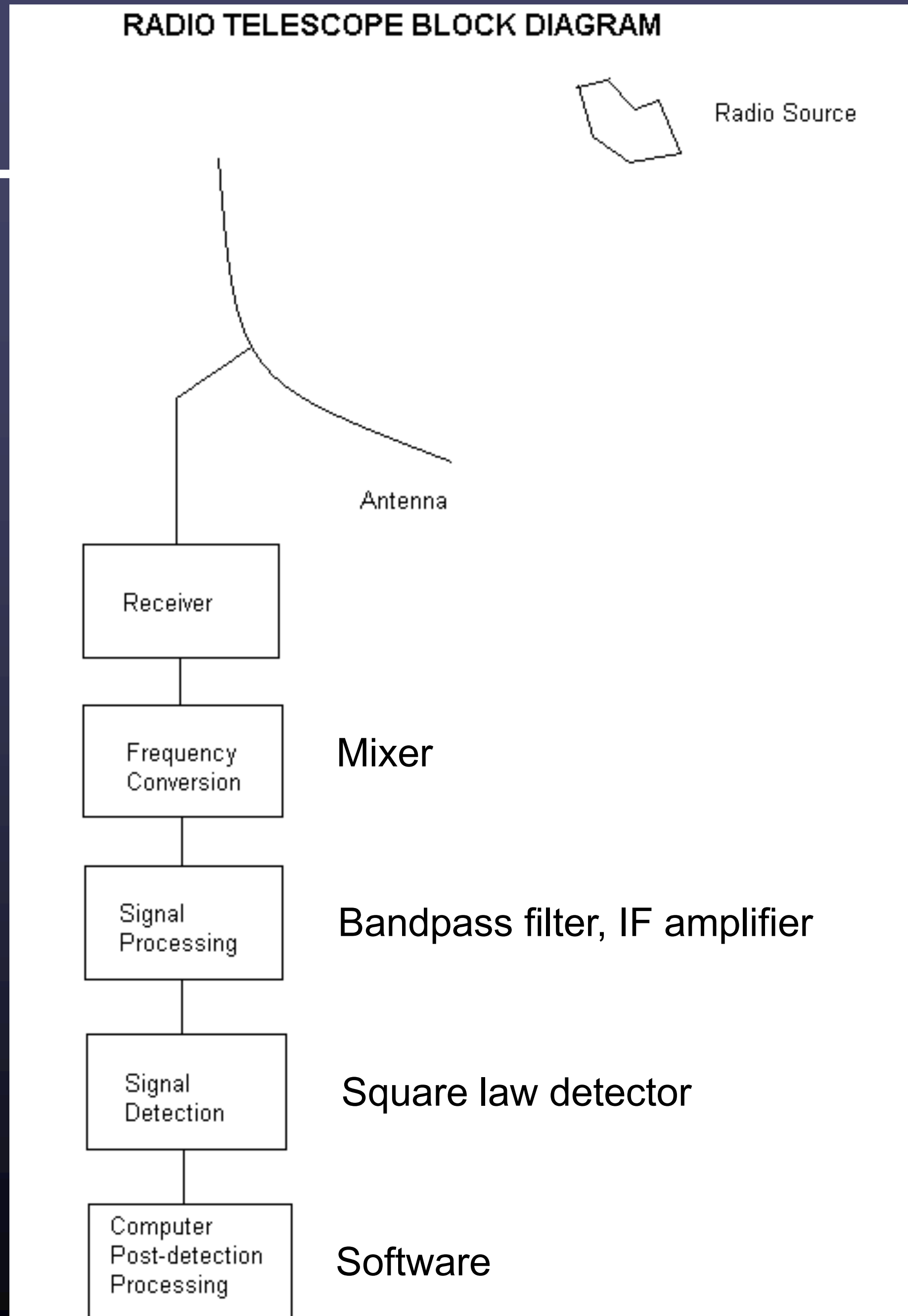


Fourier Transforms



Fourier Transforms




RADIO TELESCOPE BLOCK DIAGRAM
Radio Source
Antenna
Receiver
Frequency Conversion
Mixer
Signal Processing
Bandpass filter, IF amplifier
Signal Detection
Square law detector
Computer Post-detection Processing
Software

E.g., pre-upgrade VLA observing at 4.8 GHz (C band)

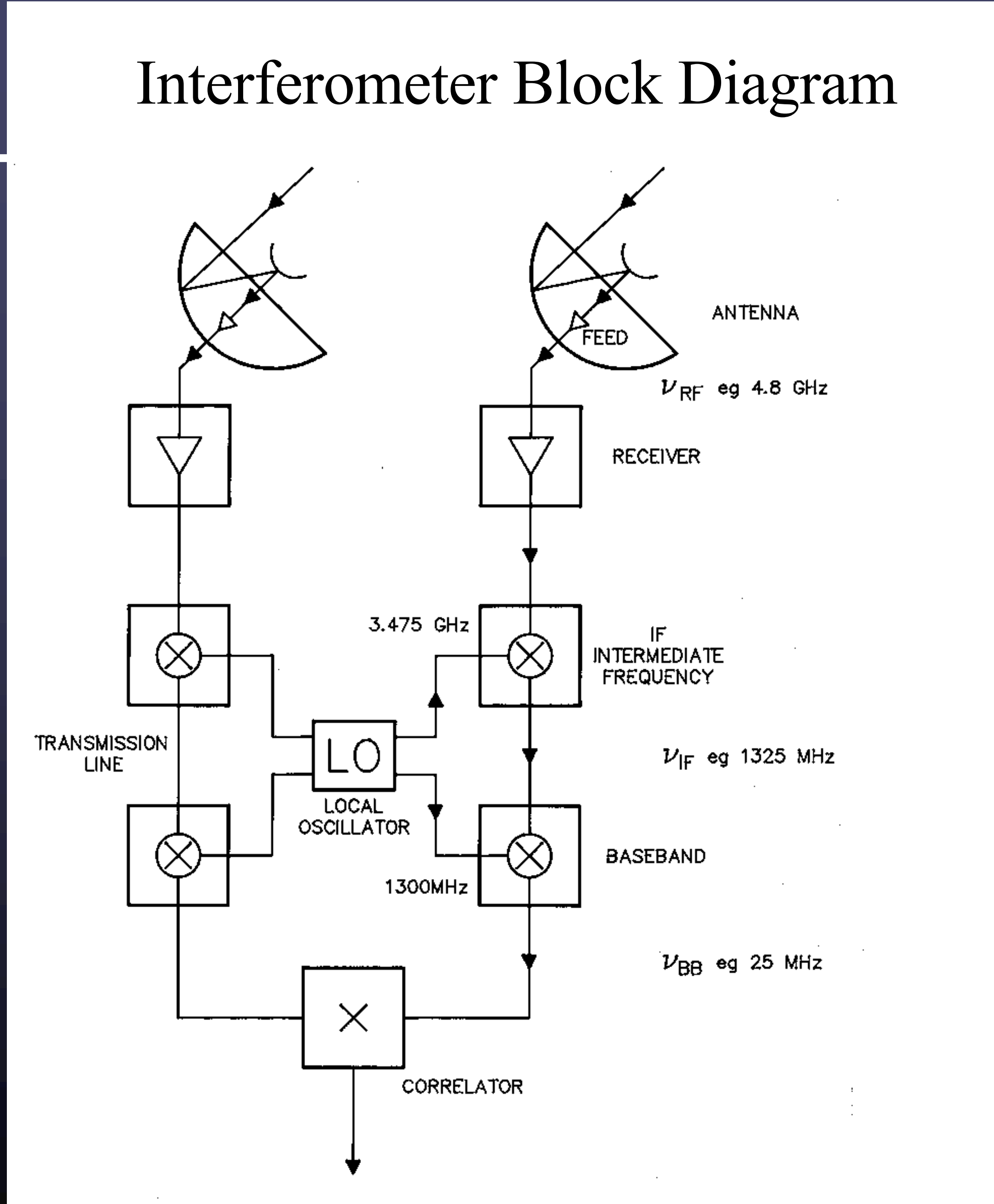
Antenna

Front End

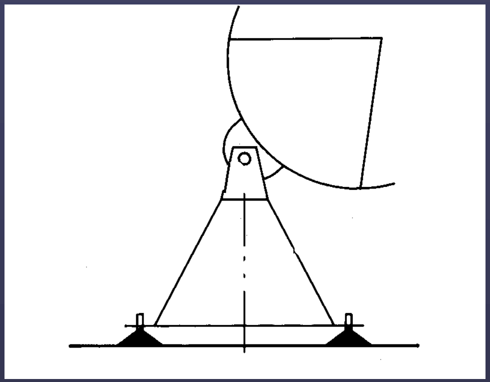
IF

Back End

Correlator



Importance of the Antenna Elements



- Antenna amplitude pattern causes amplitude to vary across the source.
- Antenna phase pattern causes phase to vary across the source.
- Polarization properties of the antenna modify the apparent polarization of the source.
- Antenna pointing errors can cause time varying amplitude and phase errors.
- Variation in noise pickup from the ground can cause time variable amplitude errors.
- Deformations of the antenna surface can cause amplitude and phase errors, especially at short wavelengths.

General Antenna Types

Wavelength > 1 m (approx)

Wire Antennas

Dipole

$A_e = G\lambda^2/4\pi$

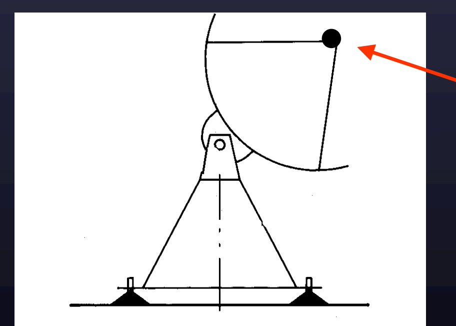
Yagi

Helix

or arrays of these

Wavelength < 1 m (approx)

Reflector antennas



Wavelength = 1 m (approx) Hybrid antennas (wire reflectors or feeds)

Basic Antenna Formulas

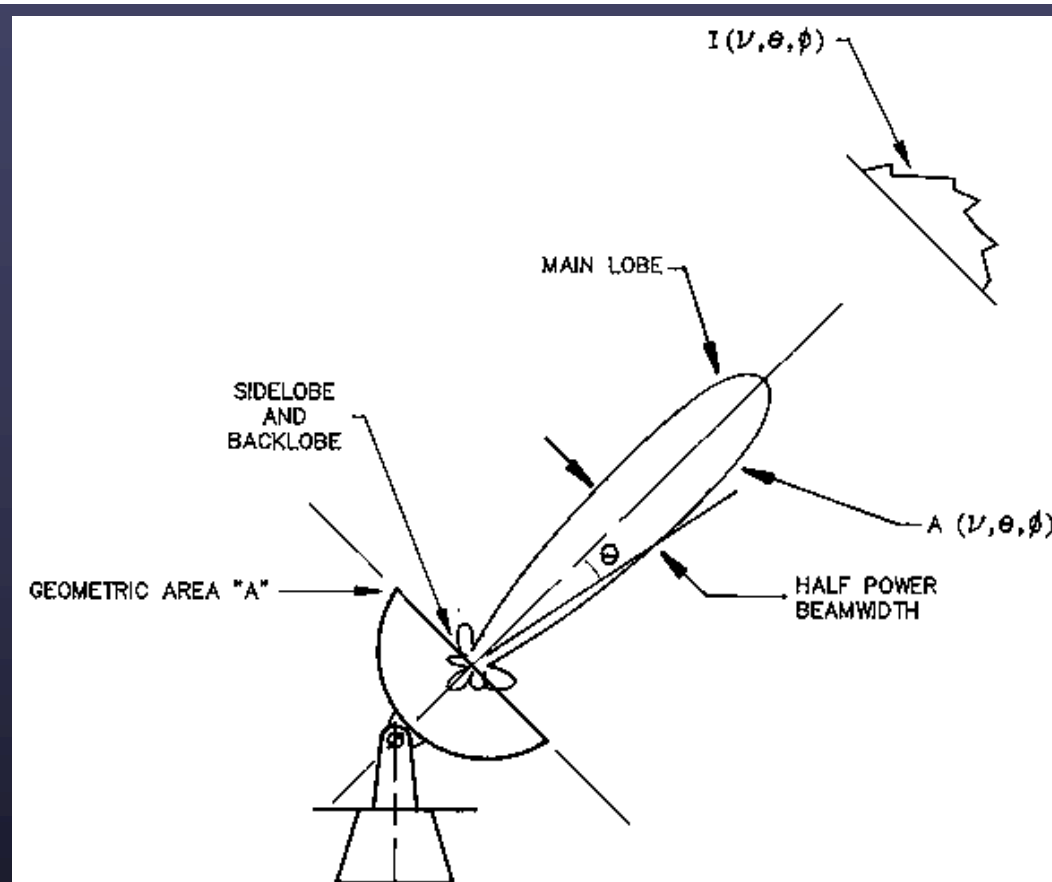
Effective collecting area $A(\nu,\theta,\phi)$ m^2

On-axis response $A_e = \eta A$

η = aperture efficiency

Normalized pattern (primary beam)

$\mathcal{A}(\nu,\theta,\phi) = A(\nu,\theta,\phi)/A_e$



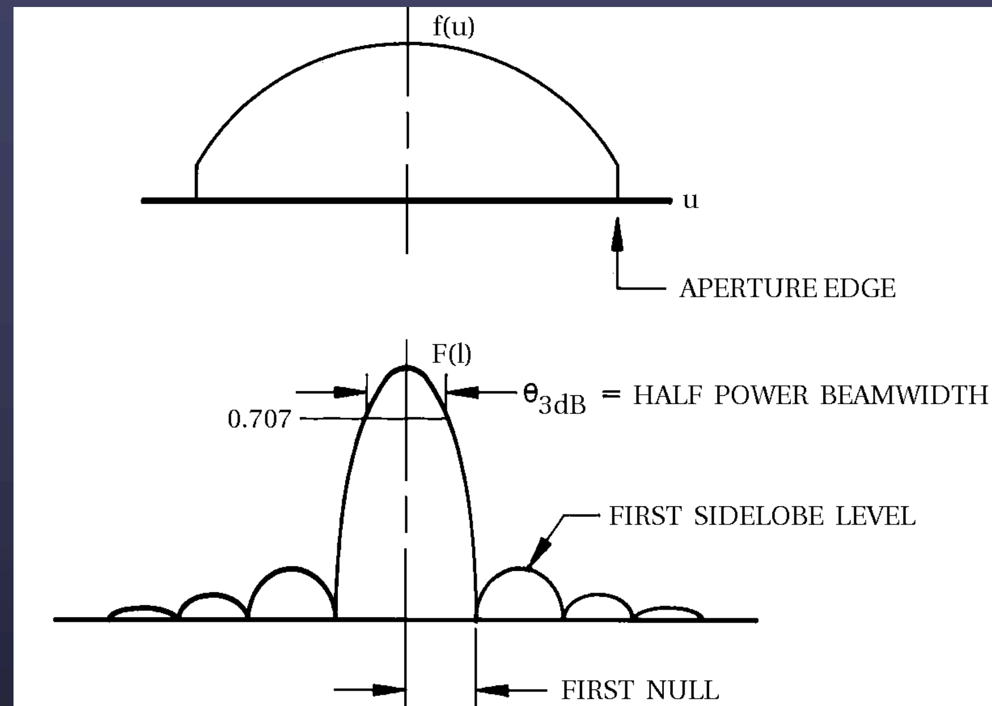
Beam solid angle $\Omega_A = \iint_{\text{all sky}} \mathcal{A}(\nu,\theta,\phi)\, d\Omega$

$A_e\, \Omega_A = \lambda^2$

Aperture-Beam Fourier Transform Relationship

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

u,v = aperture coordinates (wavelengths)



$F(l,m)$ = complex far-field voltage pattern

$l = \sin\theta\cos\phi$, $m = \sin\theta\sin\phi$

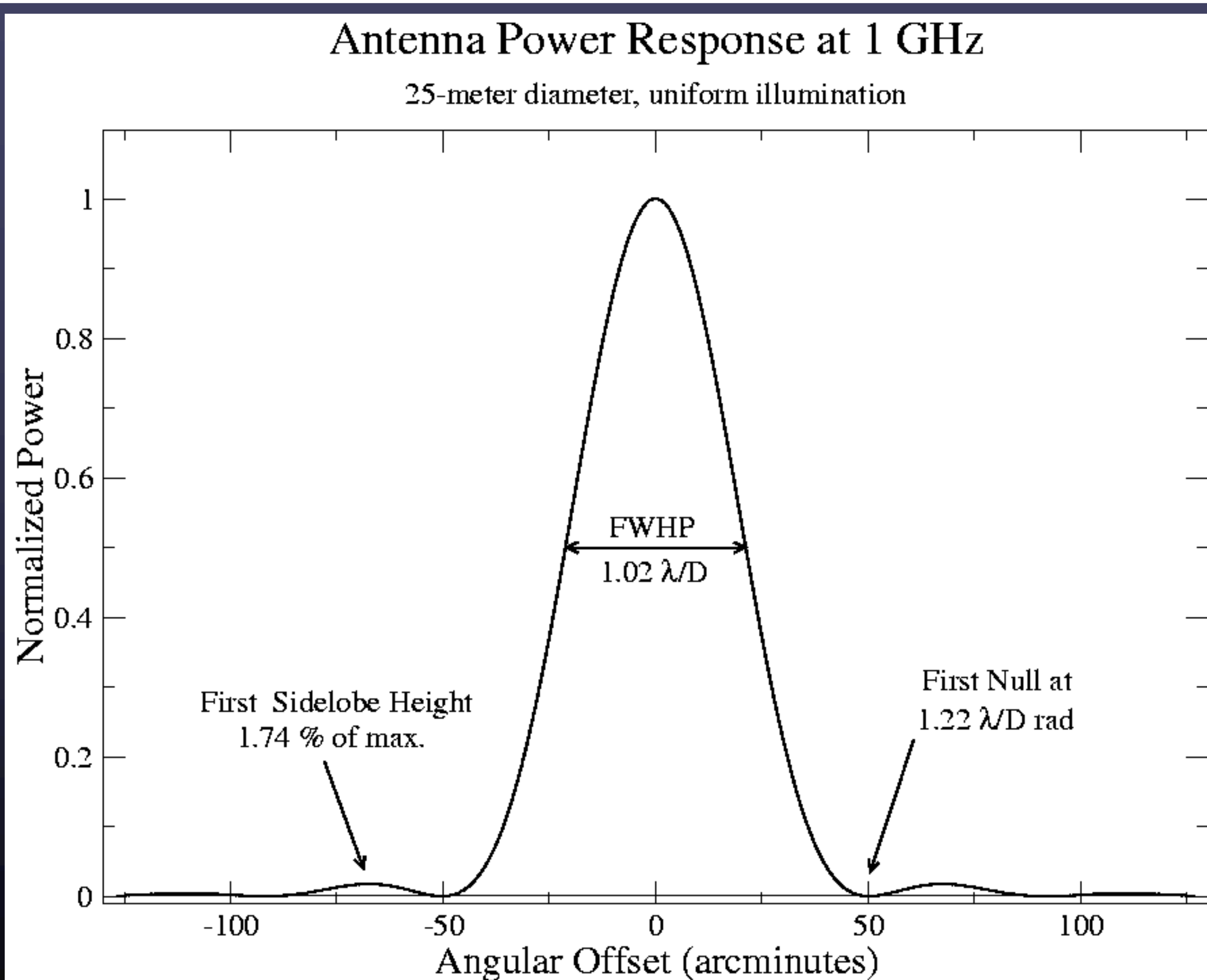
$F(l,m) = \iint_{aperture} f(u,v)\exp(2\pi i(ul+vm))dudv$

$f(u,v) = \iint_{hemisphere} F(l,m)\exp(-2\pi i(ul+vm))dldm$

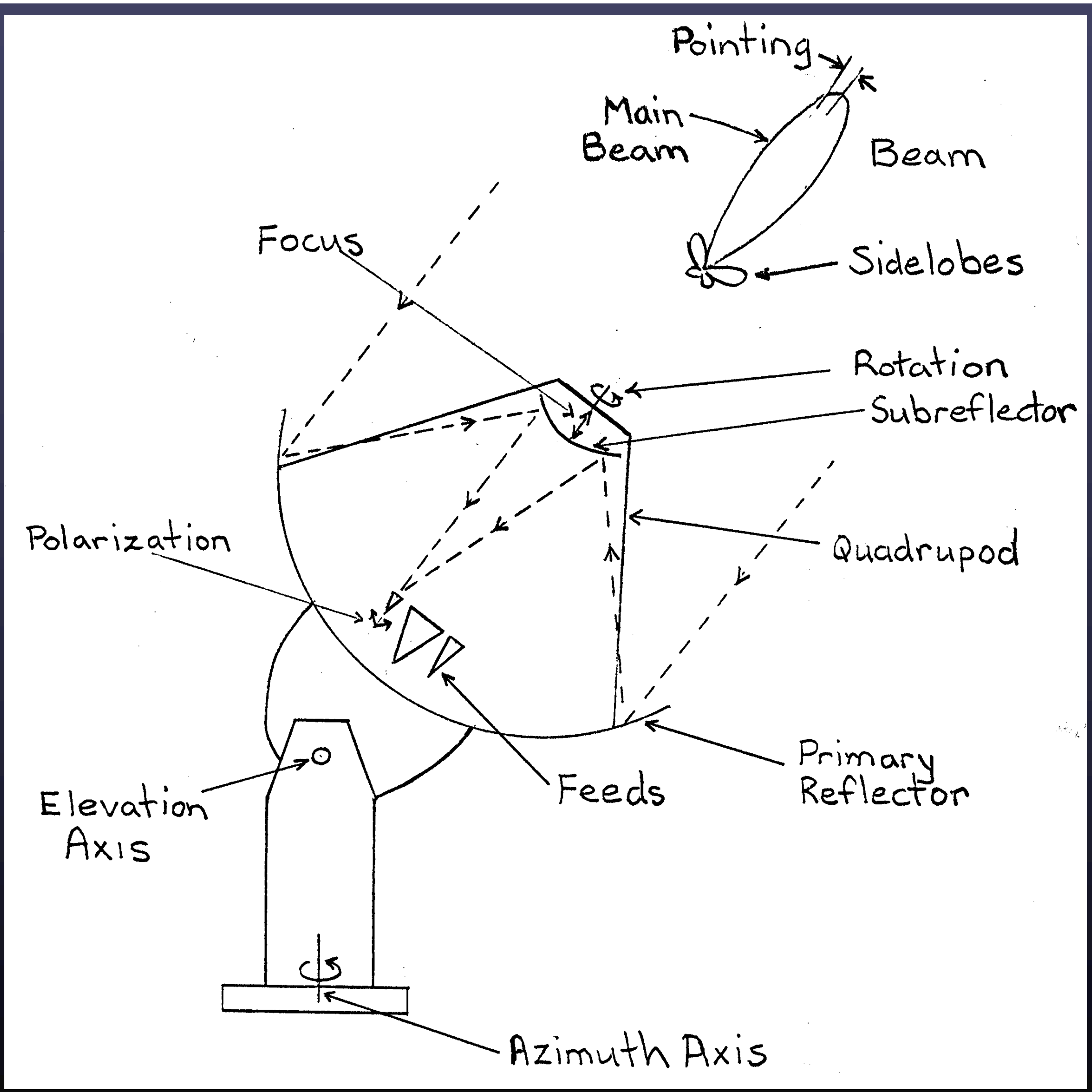
For VLA: $\theta_{3dB} = 1.02/D$, First null = $1.22/D$,

D = reflector diameter in wavelengths

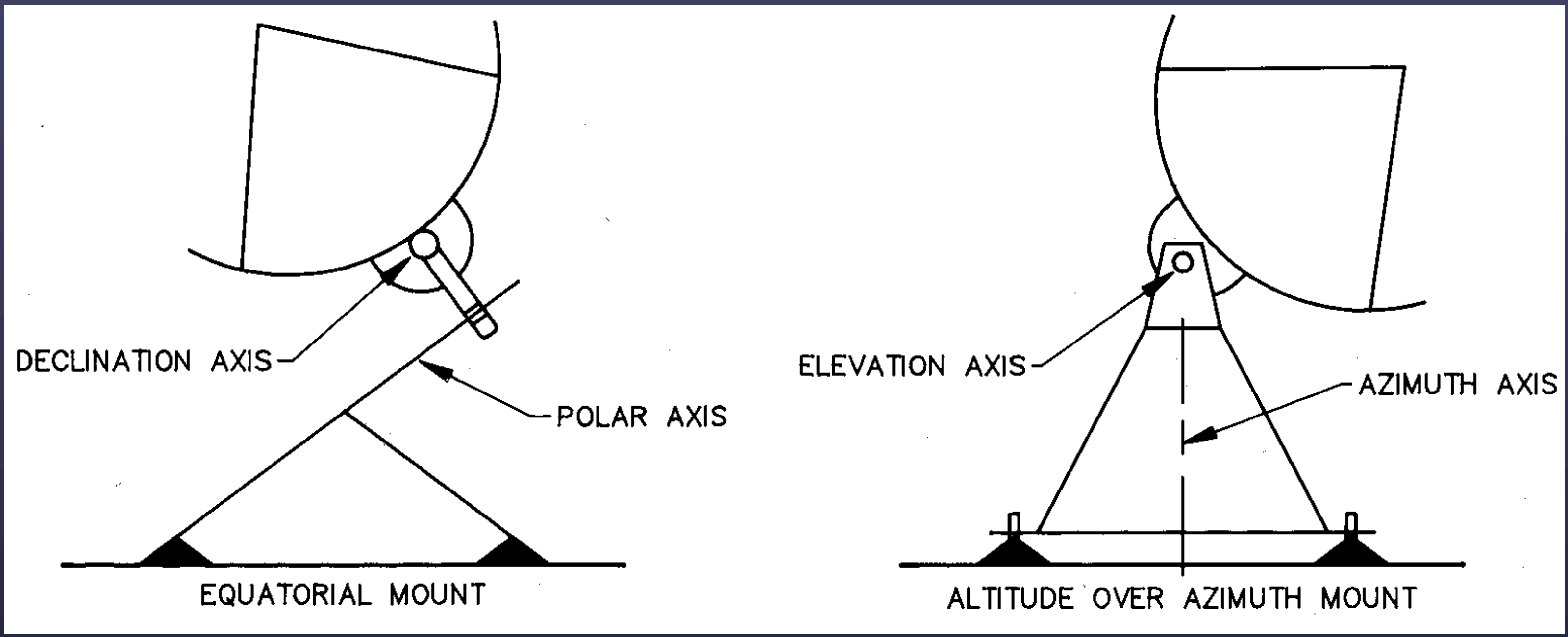
The Standard Parabolic Antenna Response



Primary Antenna Key Features



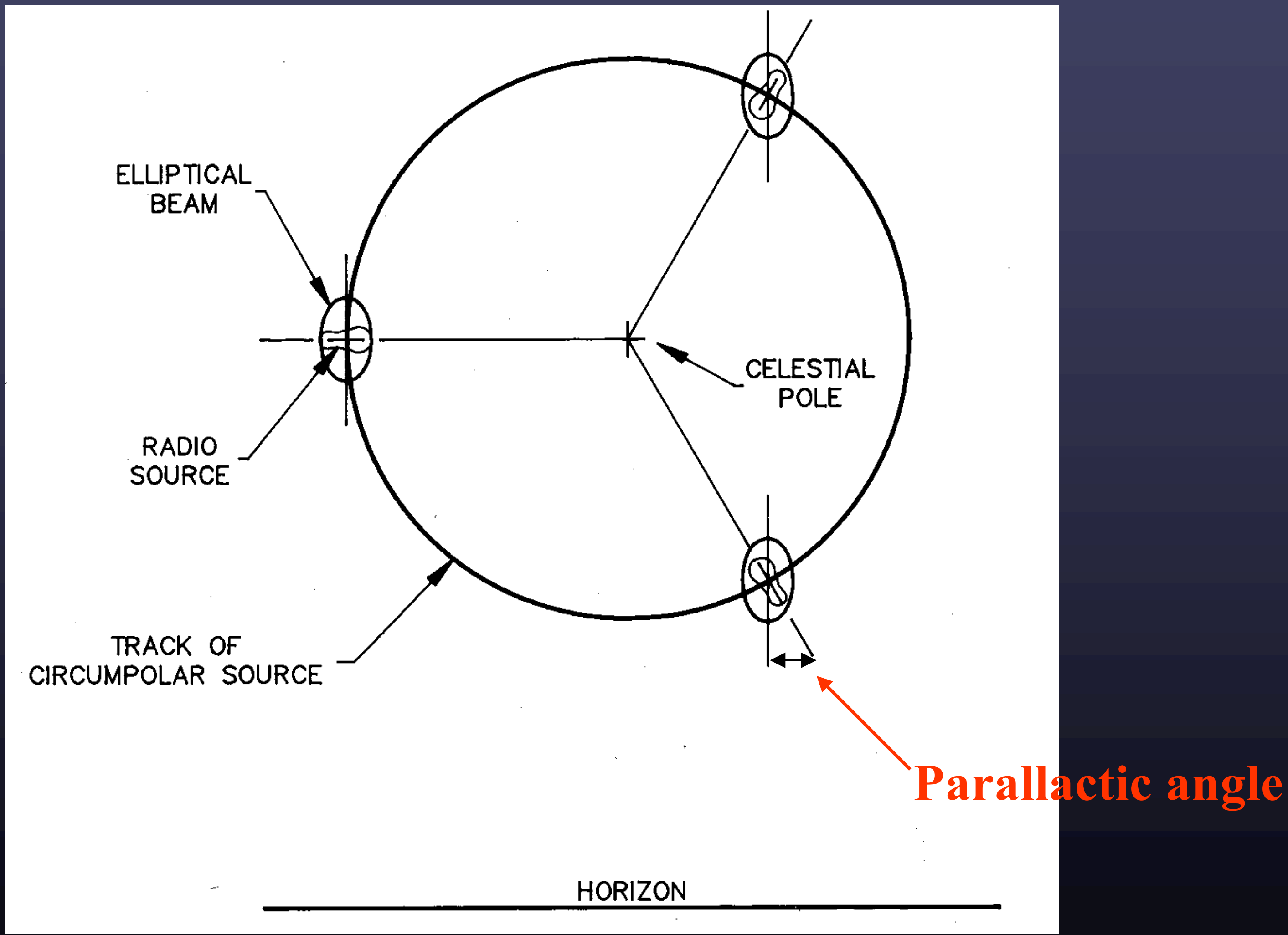
Types of Antenna Mount



+ Beam does not rotate
+ Better tracking accuracy
– Higher cost
– Poorer gravity performance
– Non-intersecting axis

+ Lower cost
+ Better gravity performance
– Beam rotates on the sky

Beam Rotation on the Sky



Reflector Types

Prime focus
(GMRT)

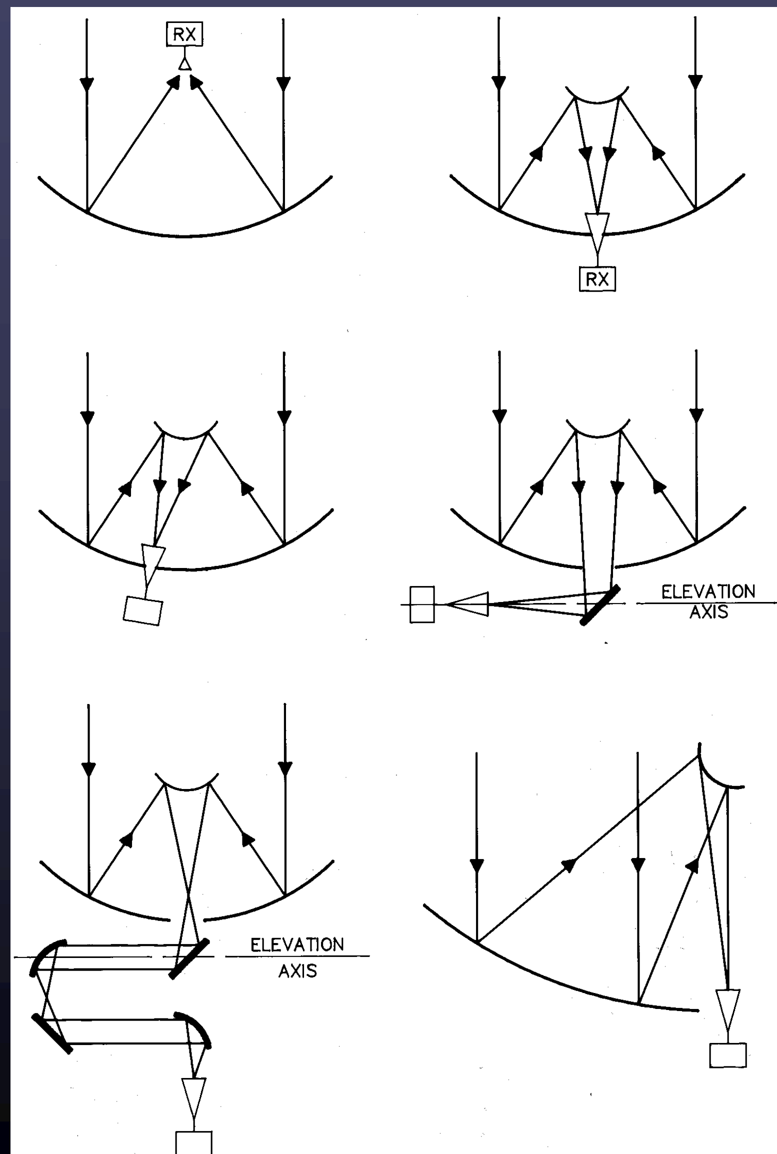
Cassegrain focus
(AT)

Offset Cassegrain
Naysmith
(VLA)

(OVRO)

Beam Waveguide
(NRO)
(ATA)

Dual Offset



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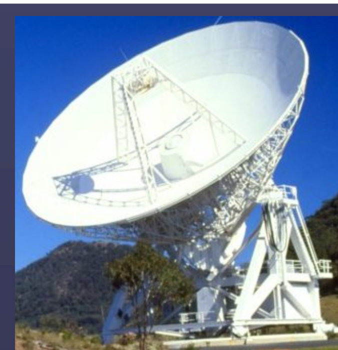
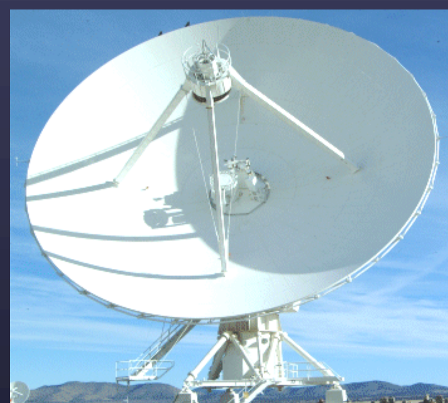
Reflector Types

Prime focus
(GMRT)



Cassegrain focus
(AT)

Offset Cassegrain
Naysmith
(VLA)



(OVRO)

Beam Waveguide
(NRO)

Dual Offset
(ATA)

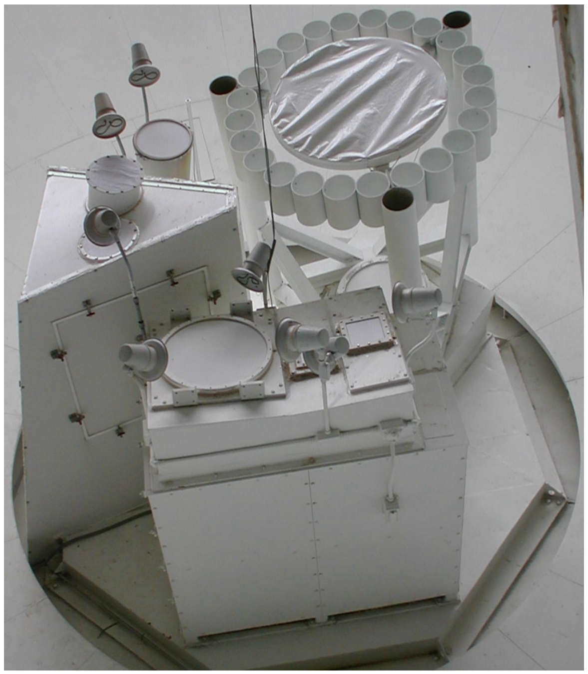
Effelsberg 100-m telescope near Bonn, Germany

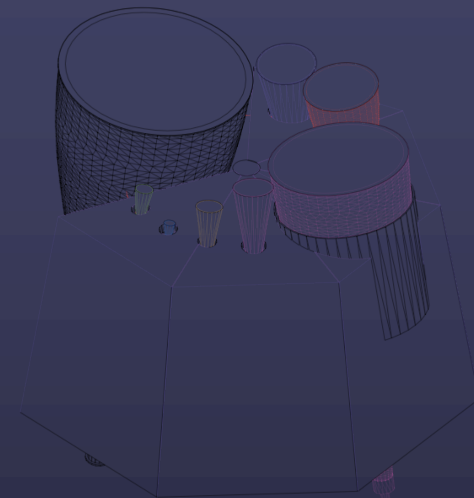
Reflector Types

Dual
Offset

Unblocked
Aperture
(GBT)

VLA and EVLA Feed System Design



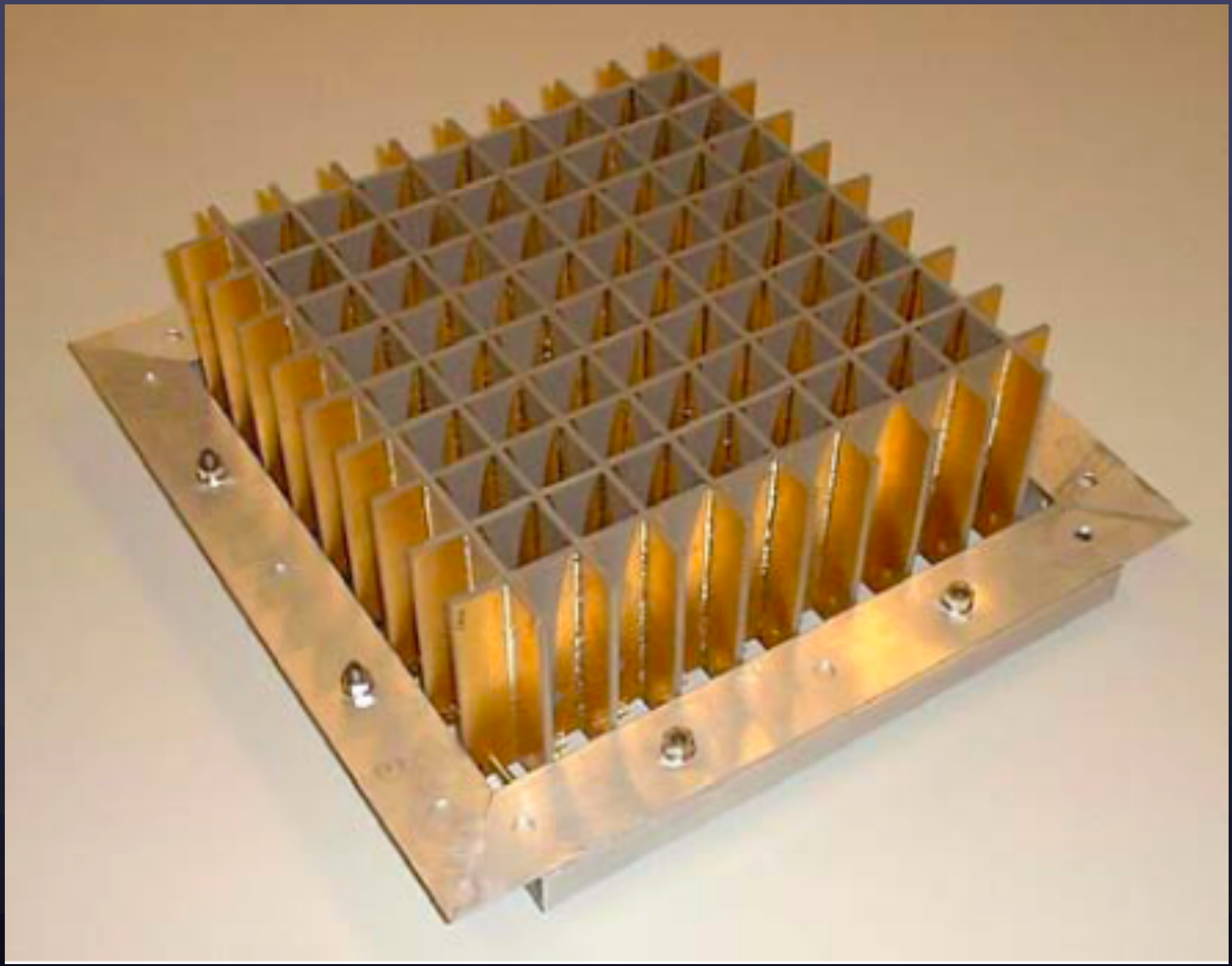


Example Feed Horn

Focal Plane Arrays

8 x 9
Array for
2-7 GHz

Ivashina
Et al.



Antenna Performance Parameters

Aperture Efficiency

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

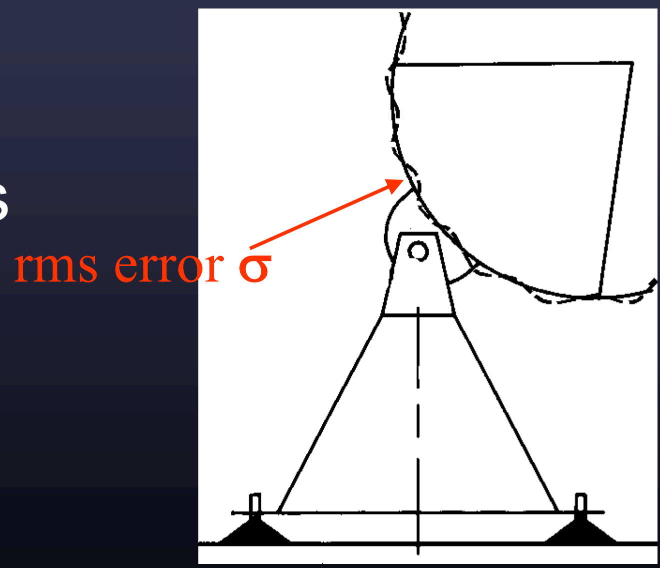
η_{sf} = reflector surface efficiency

η_{bl} = blockage efficiency

η_s = feed spillover efficiency

η_t = feed illumination efficiency

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

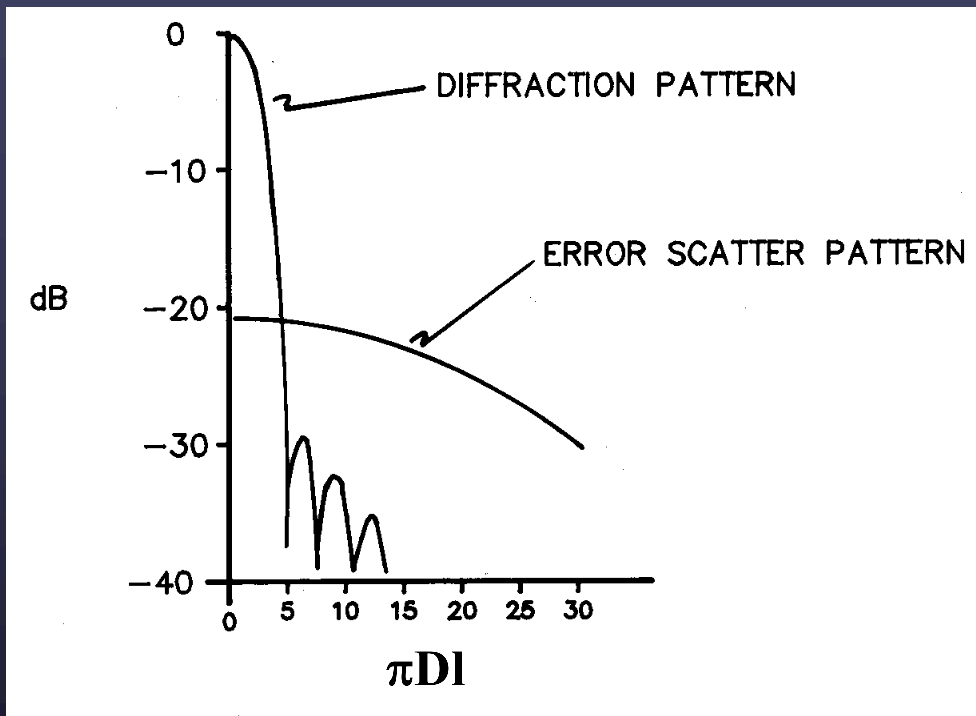


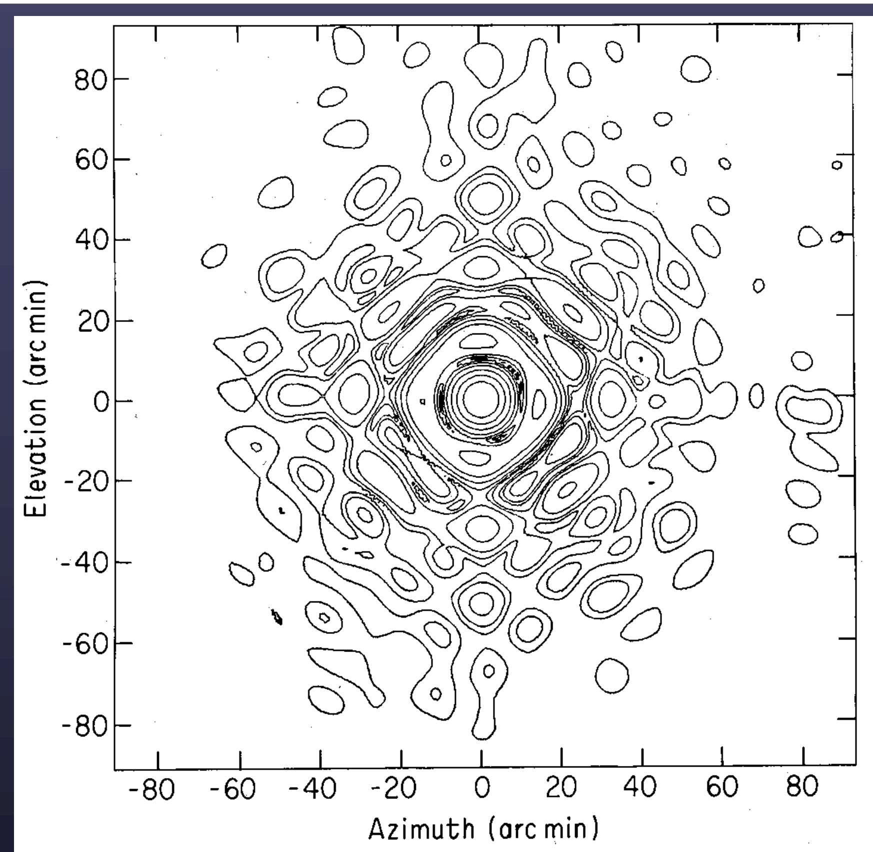
$\eta_{sf} = \exp(-(4\pi\sigma/\lambda)^2)$

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

Antenna Performance Parameters

Primary Beam





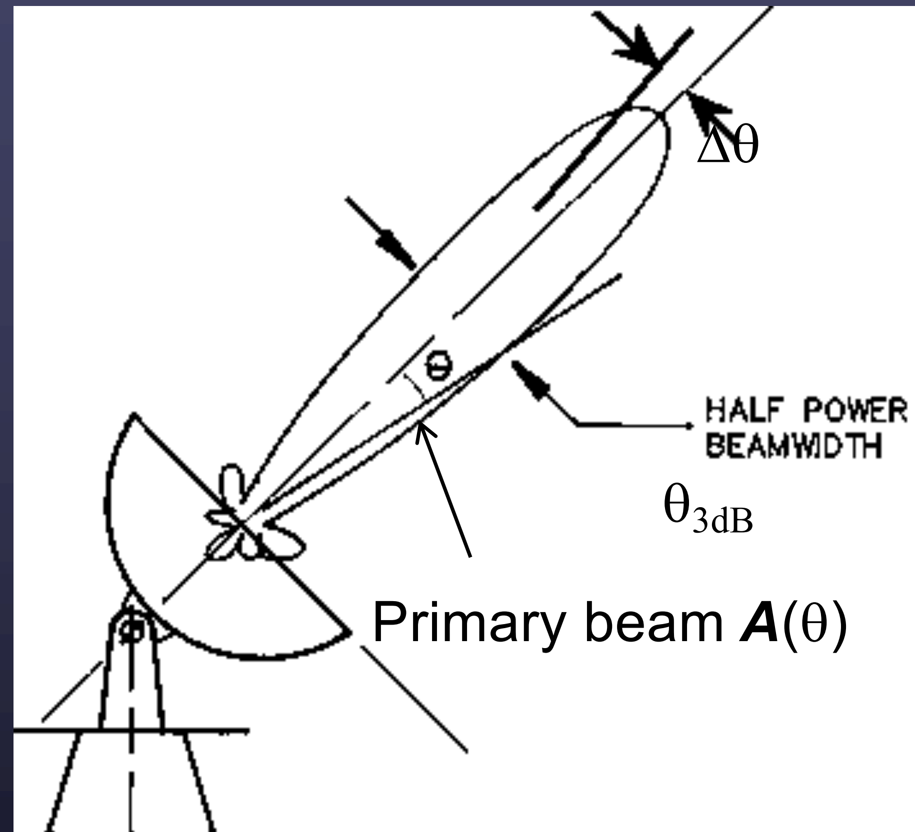
l=sin(θ), D = antenna diameter in wavelengths

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

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

contours:–3,–6,–10,–15,–20,–25, –30,–35,–40 dB

Antenna Performance Parameters



Pointing Accuracy

$\Delta\theta$ = rms pointing error

Often $\Delta\theta < \theta_{3dB}/10$ acceptable

Because $\boldsymbol{A}(\theta_{3dB}/10) \sim 0.97$

BUT, at half power point in beam

$\boldsymbol{A}(\theta_{3dB}/2 \pm \theta_{3dB}/10)/\boldsymbol{A}(\theta_{3dB}/2) = \pm 0.3$

For best VLA pointing use Reference Pointing.

$\Delta\theta$ = 3 arcsec = $\theta_{3dB}/17$ @ 50 GHz

Antenna Pointing Design

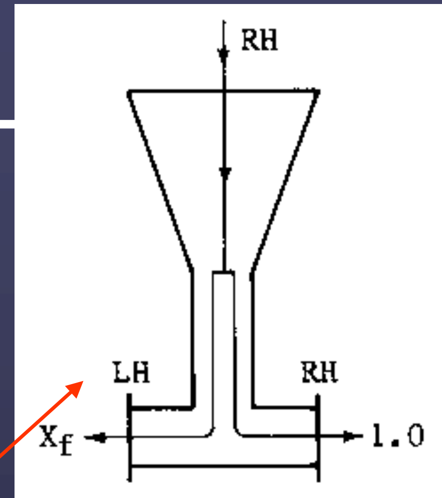
ALMA 12m Antenna

Surface: σ = 25 μm
Pointing: $\Delta\theta$ = 0.6 arcsec

Carbon fiber and invar reflector structure

Pointing metrology structure inside alidade

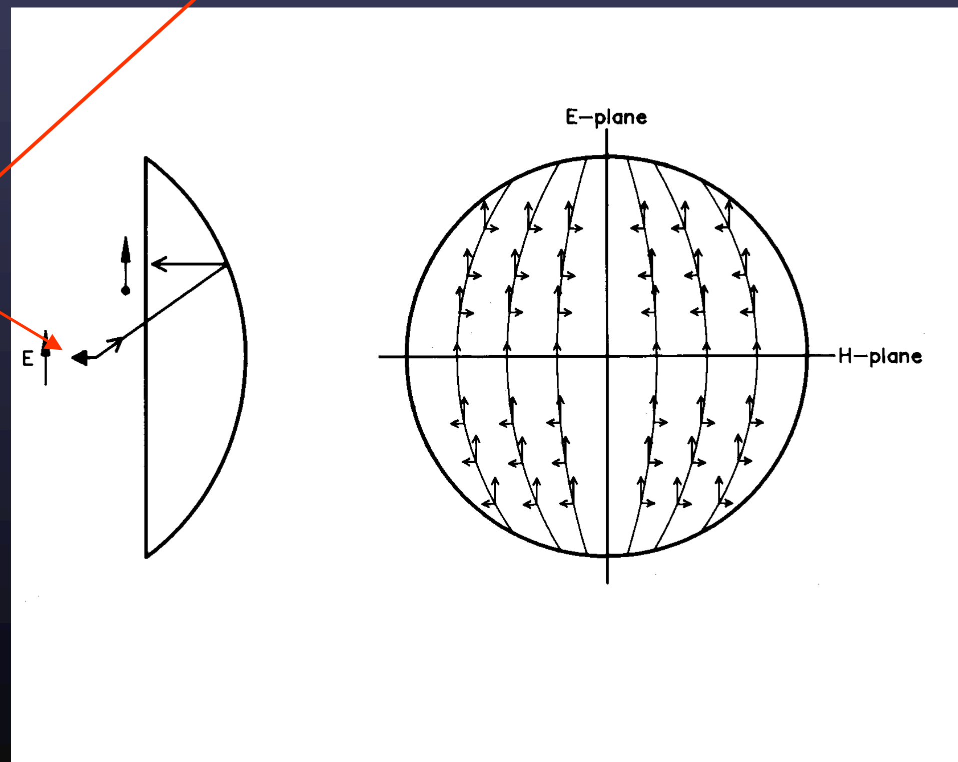
Antenna Performance Parameters



Polarization

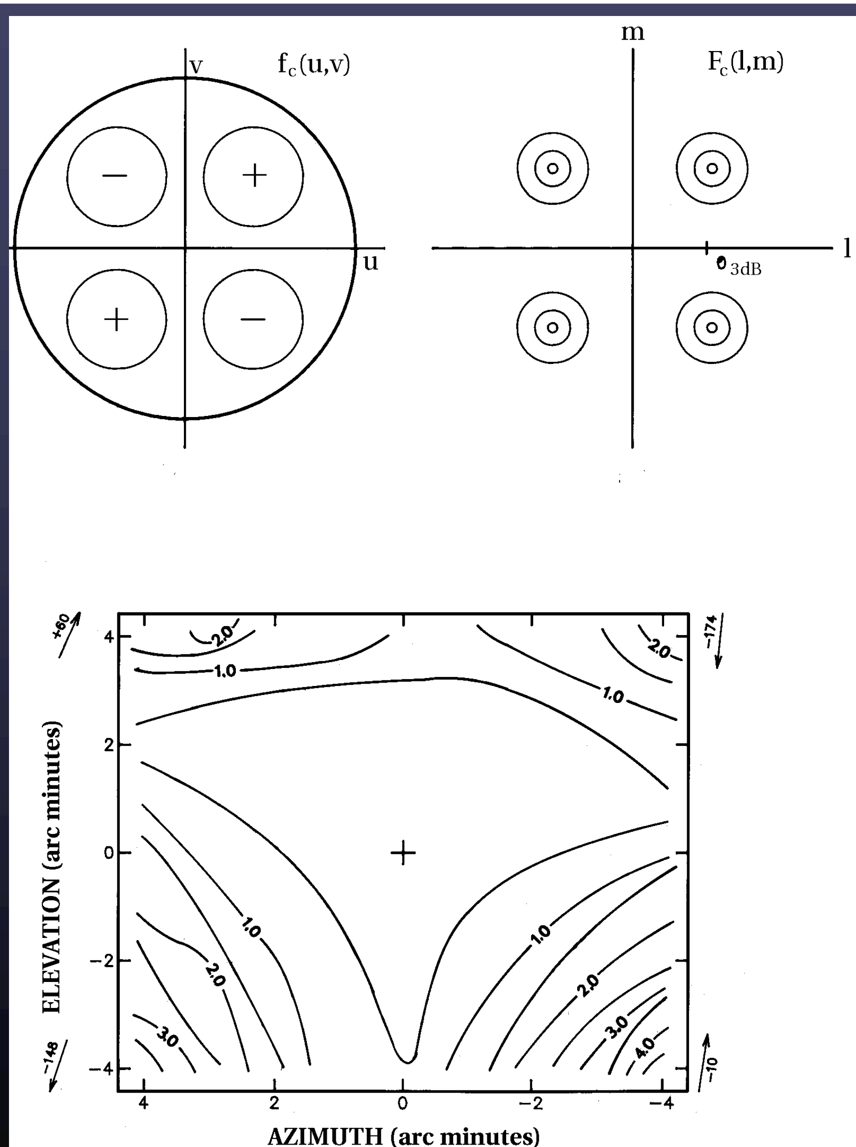
Antenna can modify the apparent polarization properties of the source:

- Symmetry of the optics
- Quality of feed polarization splitter
- Circularity of feed radiation patterns
- Reflections in the optics
- Curvature of the reflectors



Off-Axis Cross Polarization

Cross polarized aperture distribution



Cross polarized primary beam

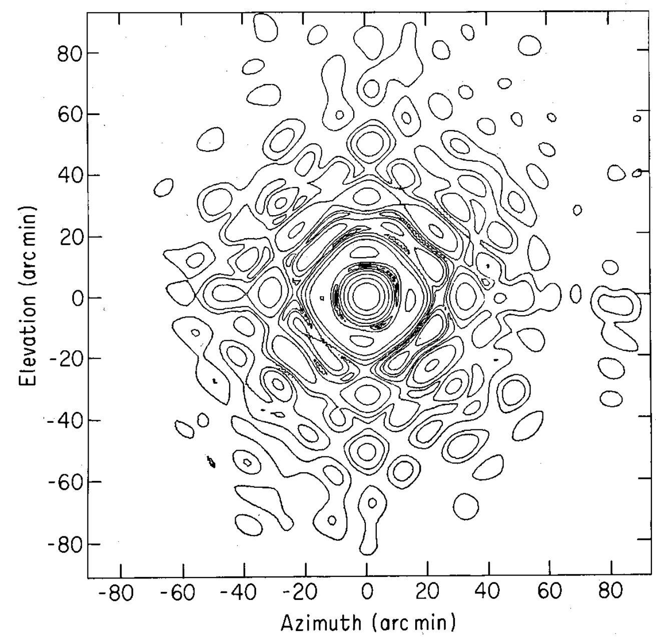
VLA 4.8 GHz cross polarized primary beam

Antenna Holography

VLA 4.8 GHz

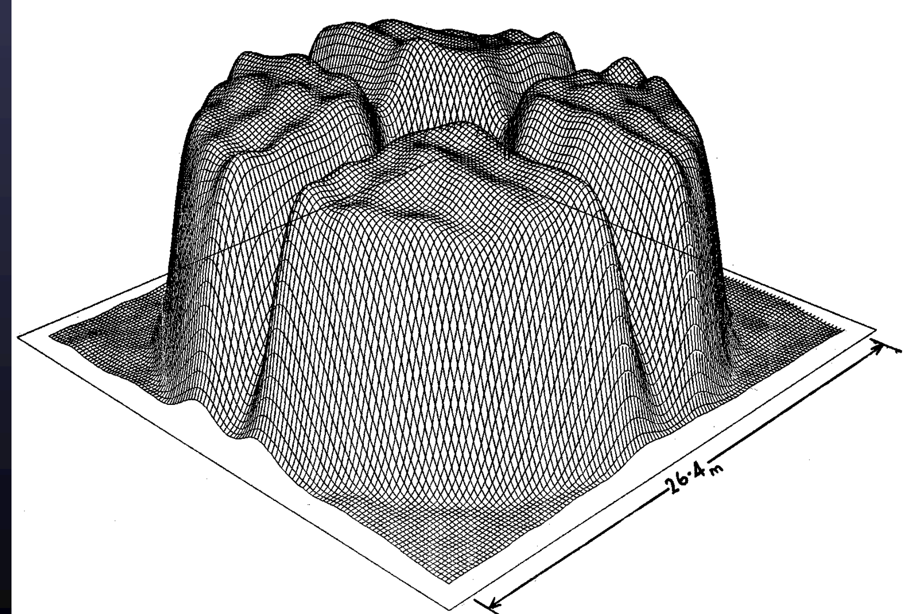
Far field pattern amplitude

Phase not shown



Aperture field distribution amplitude.

Phase not shown



Other Concerns

- Pointing errors, especially at high frequencies
- Gain curves
- Atmospheric opacity corrections
- Ionospheric effects: scintillation, isoplanatic patch size

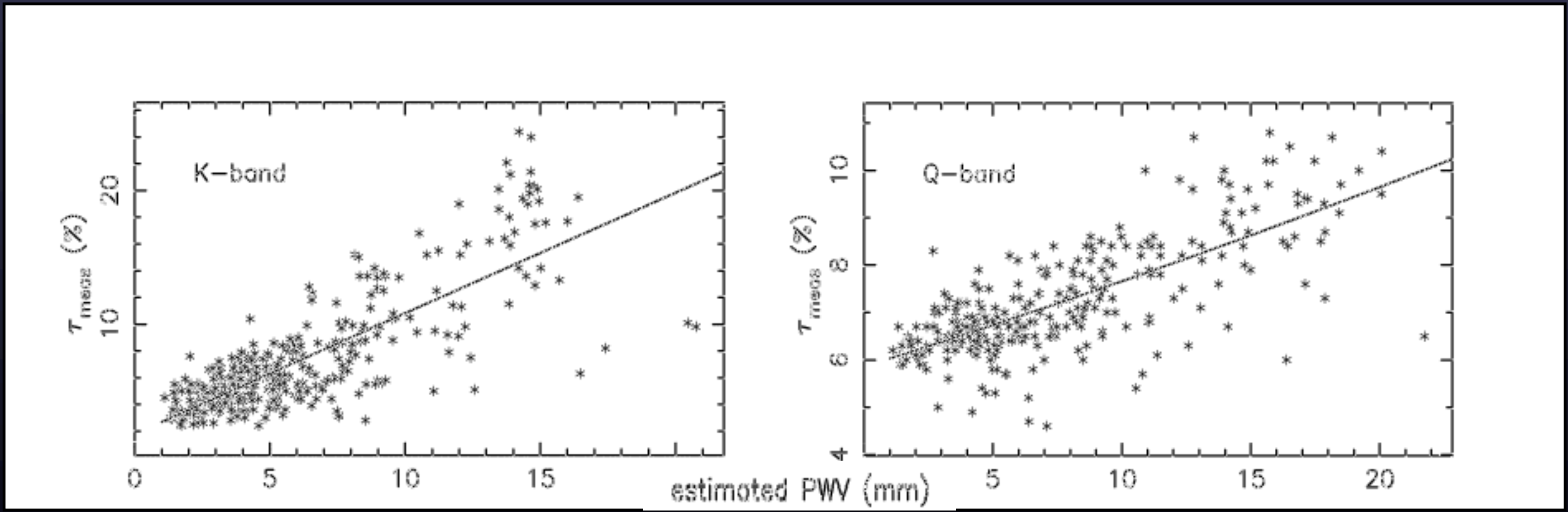
Practical concerns continued

- **Opacity corrections and tipping scans**
  - Can measure the total power detected as a function of elevation, which has contributions

$$T_{sys} = T_0 + T_{atm}(1-e^{\tau_0 a}) + T_{spill}(a)$$

and solve for τ_0.

  - Or, make use of the fact that there is a good correlation between the surface weather and τ_0 measured at the VLA (Butler 2002):

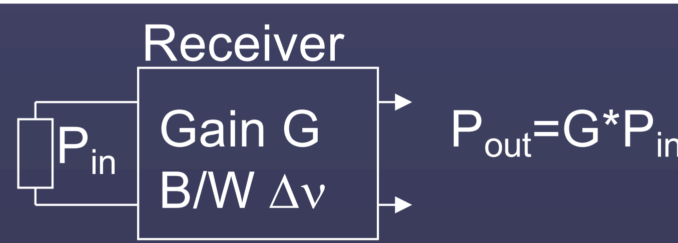


and apply this opacity correction using FILLM in AIPS

Receivers

Noise Temperature

Matched load Temp T (^oK)



Rayleigh-Jeans approximation

$P_{in} = k_B T \, \Delta\nu$,

k_B = Boltzman's constant

When observing a radio source $T_{total} = T_A + T_{sys}$

Tsys = system noise when not looking at a discrete radio source

T_A = source antenna temperature

$T_A = \eta AS/(2k_B)$ S = source flux (Jy)

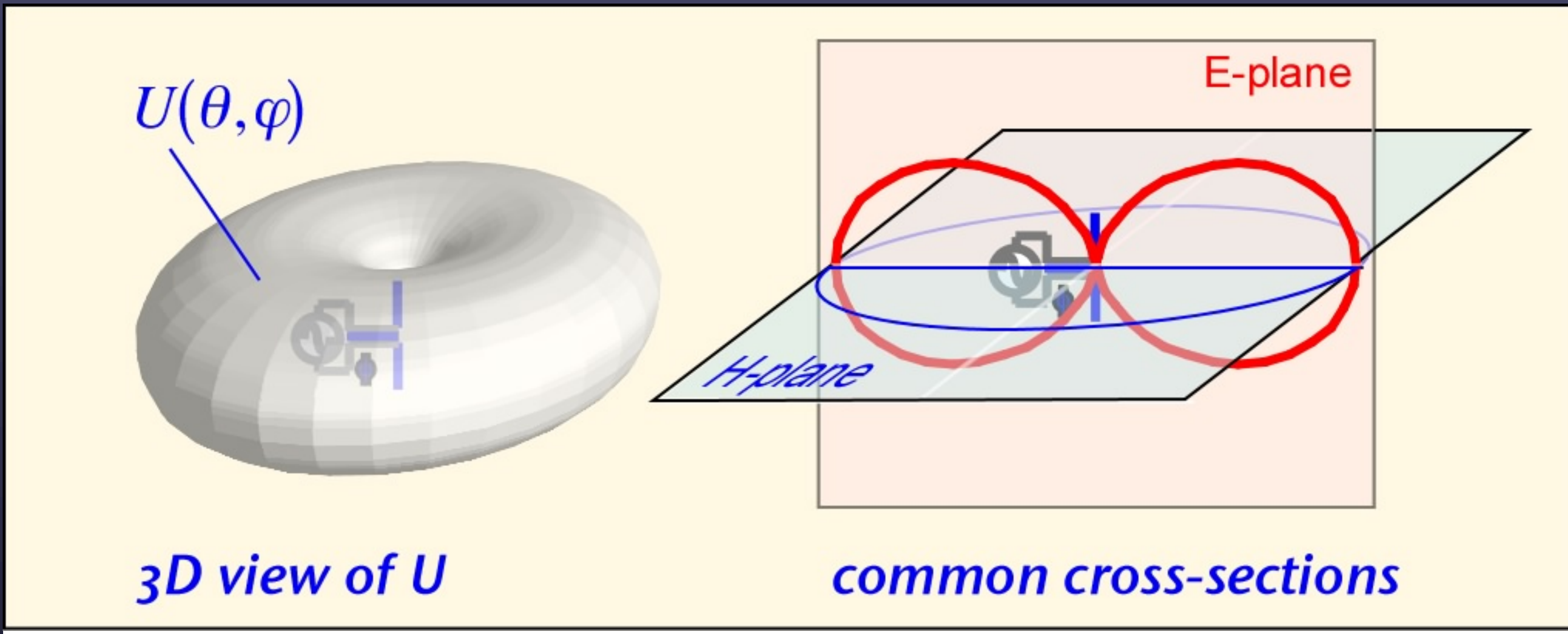
SEFD = system equivalent flux density

SEFD = Tsys/K (Jy)

VLA Sensitivities

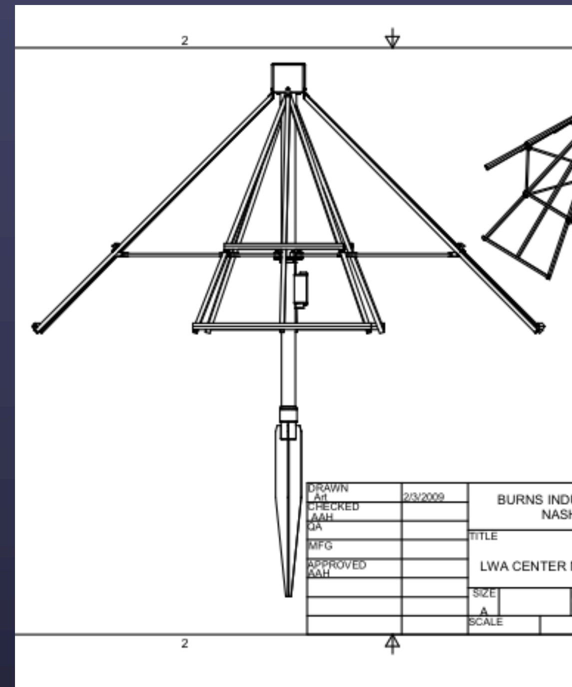
Band (GHz)	η	T_{sys}	SEFD
1-2	.50	21	236
2-4	.62	27	245
4-8	.60	28	262
8-12	.56	31	311
12-18	.54	37	385
18-26	.51	55	606
26-40	.39	58	836
40-50	.34	78	1290

Hertz Dipole



$A_e = G\lambda^2/4\pi$ G=1.5 for Hertz Dipole
G = 2.5 at 20 MHz for LWA
G = 4.0 at 60 MHz for LWA

LWA Antenna


2
DRAWN
Art
2/3/2009
CHECKED
AAH
QA
MFG
APPROVED
AAH
BURNS INDUS
NASHU
TITLE
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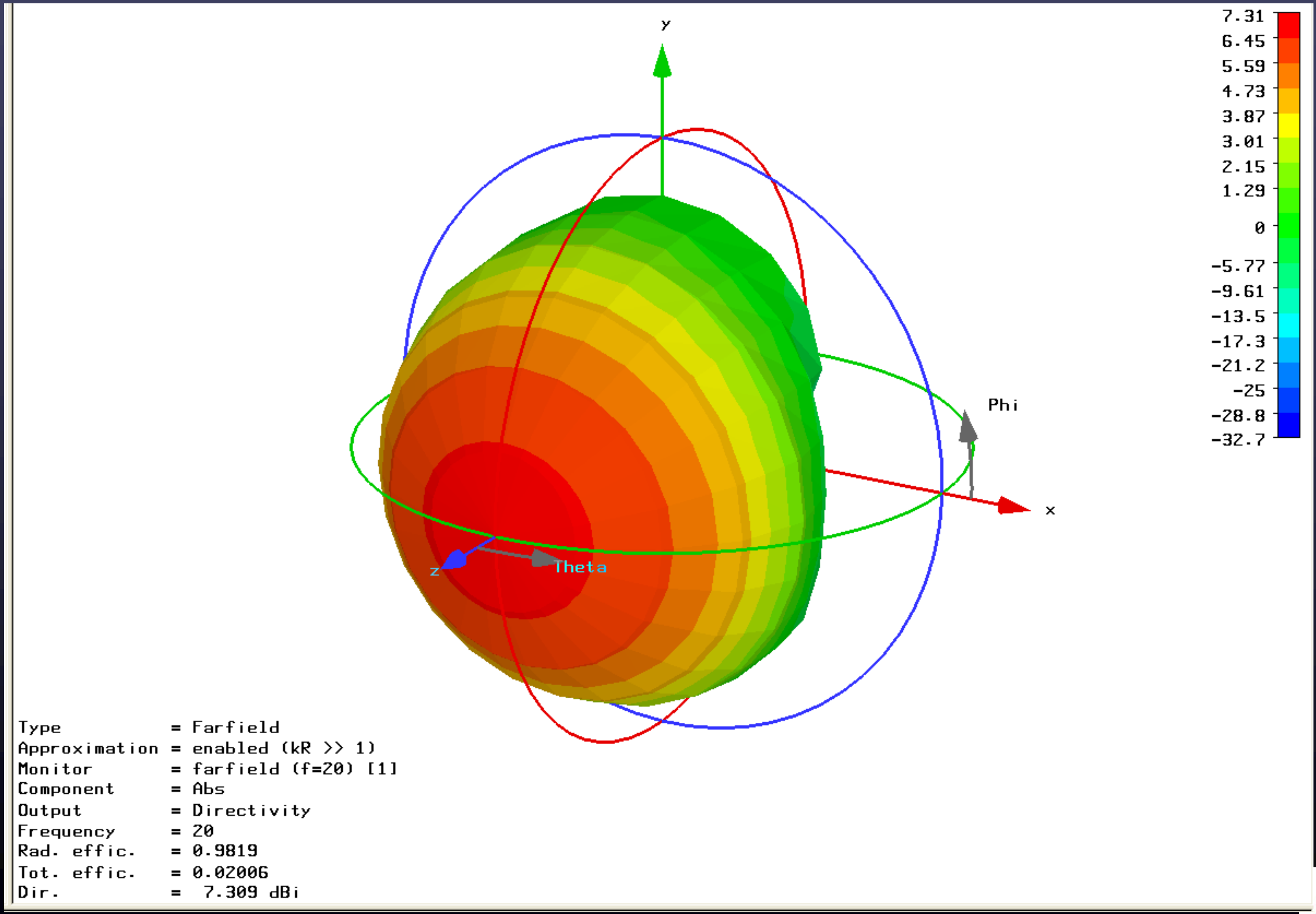
SIZE
A
SCALE
2

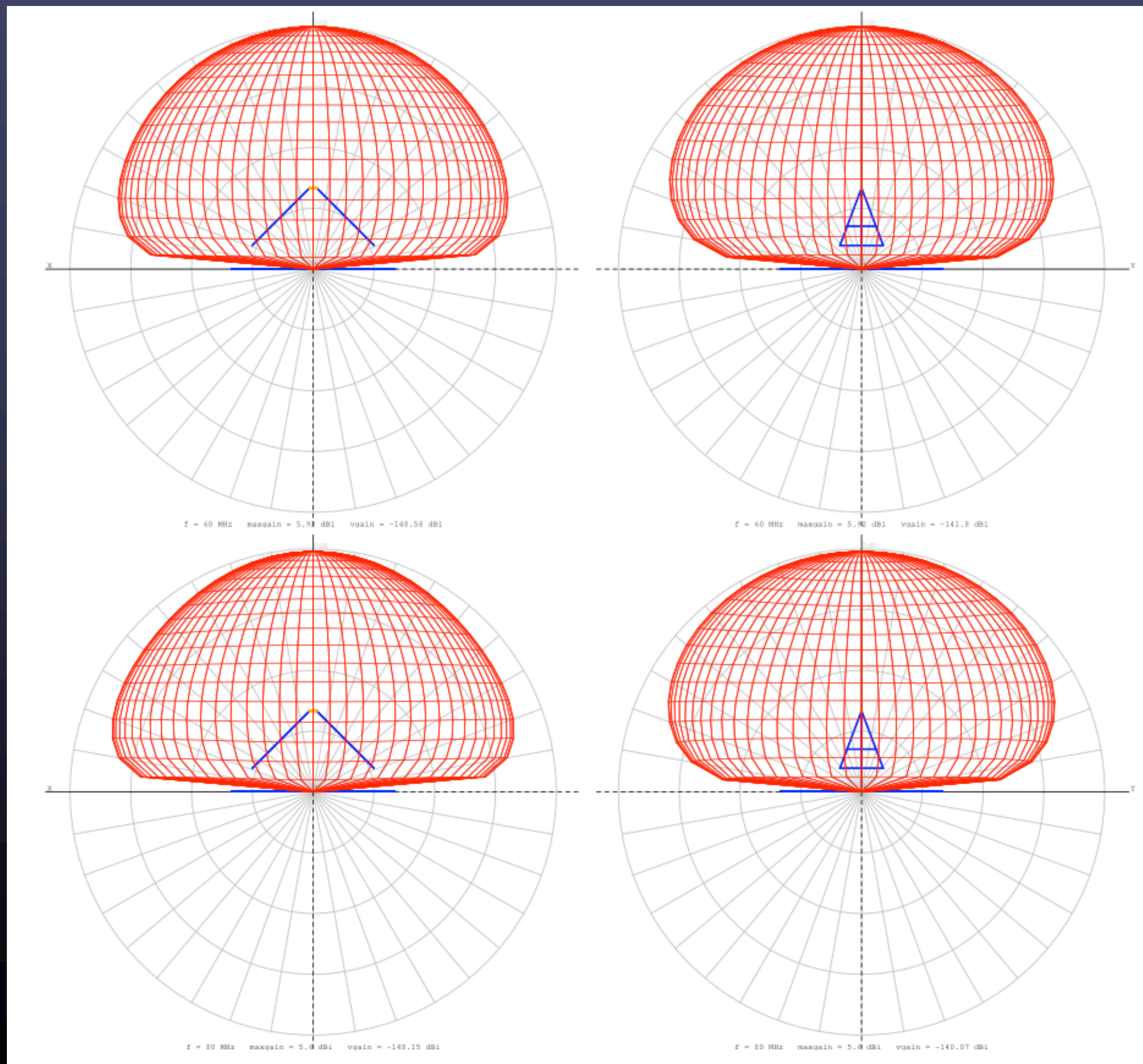
20 MHz 3D


y
x
z
Phi
Theta
7.31
6.45
5.59
4.73
3.87
3.01
2.15
1.29
0
-5.77
-9.61
-13.5
-17.3
-21.2
-25
-28.8
-32.7
Type = Farfield
Approximation = enabled (kR >> 1)
Monitor = farfield (f=20) [1]
Component = Abs
Output = Directivity
Frequency = 20
Rad. effic. = 0.9819
Tot. effic. = 0.02006
Dir. = 7.309 dBi

E and H-Plane Antenna Pattern

60 MHz

80 MHz



Further Reading

http://www.nrao.edu/whatisra/mechanisms.shtml
http://www.nrao.edu/whatisra/
www.nrao.edu

Synthesis Imaging in Radio Astronomy
ASP Vol 180, eds Taylor, Carilli & Perley