Antennas in Radio Astronomy

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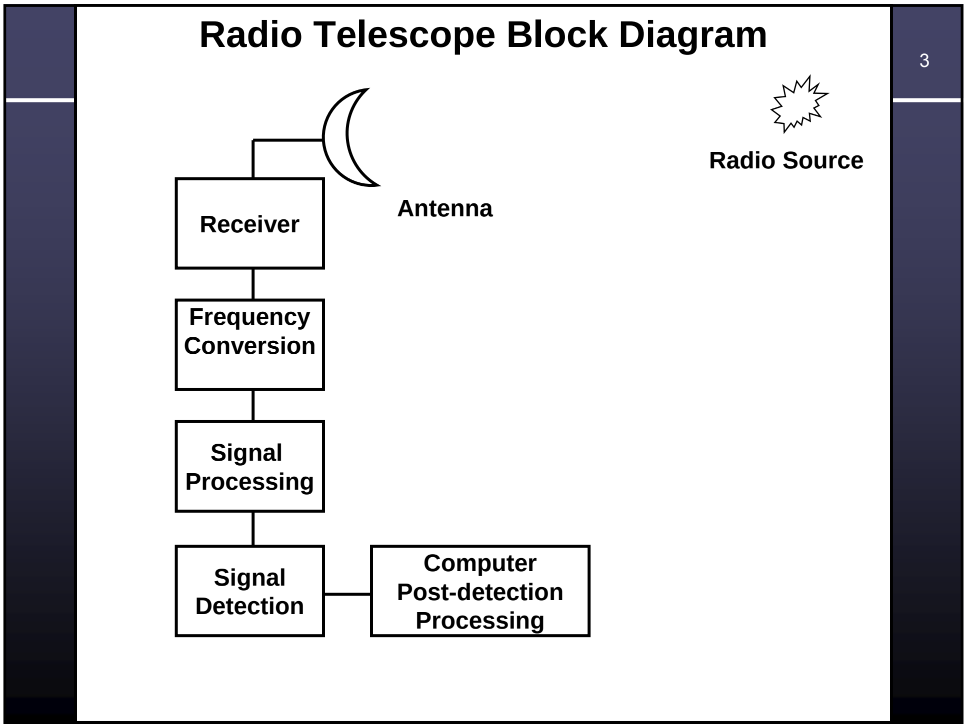
Outline

- Interferometer block diagram
- Antenna fundamentals
- Types of antennas
- Antenna performance parameters
- Receivers


Radio Telescope Block Diagram
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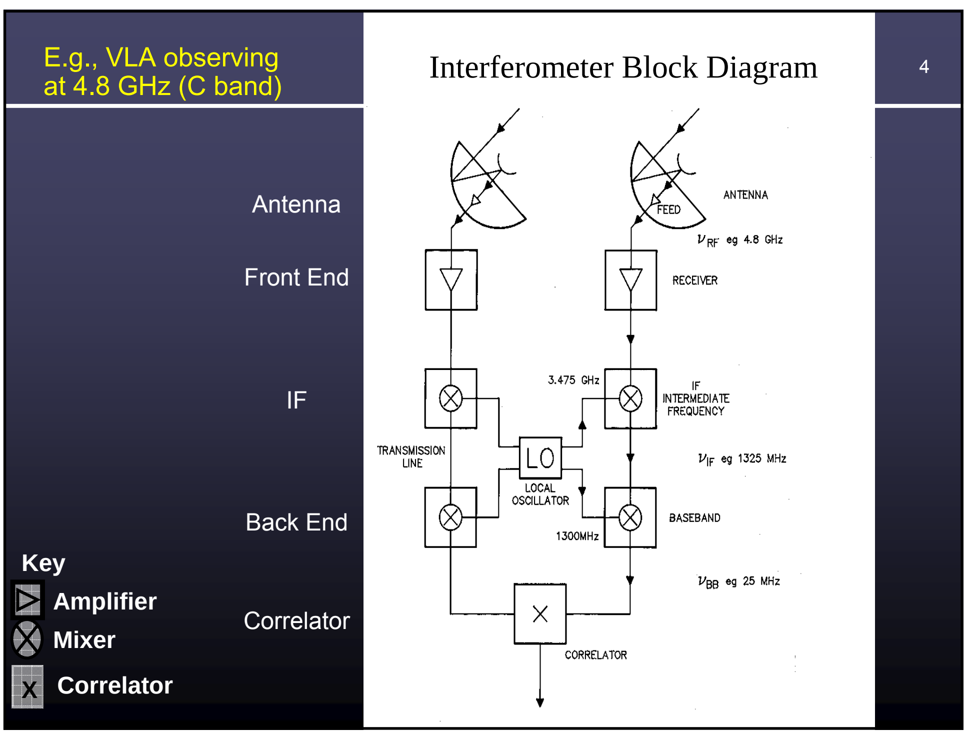
Radio Source
Antenna
Receiver
Frequency Conversion
Signal Processing
Signal Detection
Computer Post-detection Processing


E.g., VLA observing at 4.8 GHz (C band)
Interferometer Block Diagram
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Antenna
Front End
IF
Back End
Correlator
Key
Amplifier
Mixer
Correlator
ANTENNA
FEED
ν_{RF} eg 4.8 GHz
RECEIVER
3.475 GHz
IF INTERMEDIATE FREQUENCY
TRANSMISSION LINE
LO
LOCAL OSCILLATOR
ν_{IF} eg 1325 MHz
BASEBAND
1300MHz
ν_{BB} eg 25 MHz
CORRELATOR

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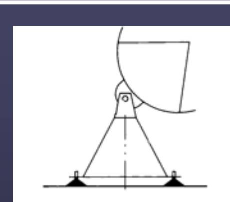
Importance of the Antenna Elements



- 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.

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General Antenna Types

Wavelength > 1 m (approx) Wire Antennas

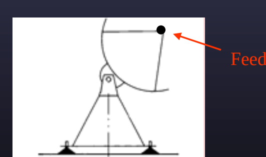
Dipole

Yagi

Helix

or arrays of these

Wavelength < 1 m (approx) Reflector antennas



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

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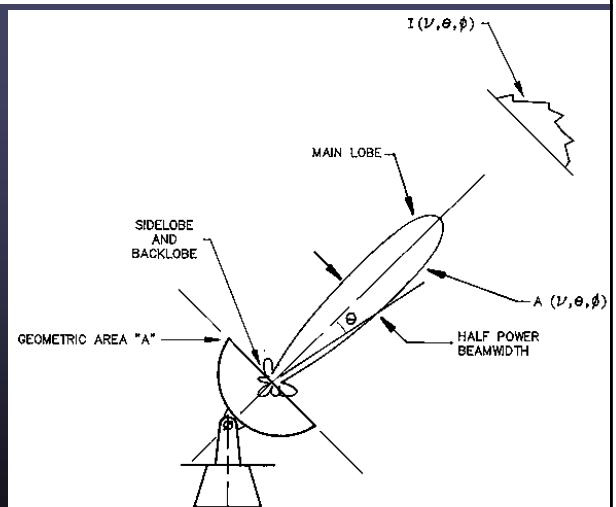
Basic Antenna Formulas

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

On-axis response $A_0 = \eta A$
η = aperture efficiency

Normalized pattern (primary beam)
$\boldsymbol{A}(\nu,\theta,\phi) = A(\nu,\theta,\phi)/A_0$

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



$A_0\, \Omega_A = \lambda^2$

λ = wavelength, ν = frequency

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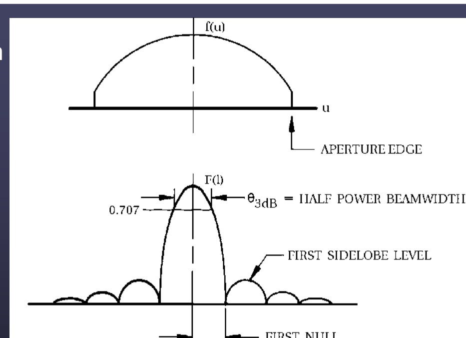
Aperture-Beam Fourier Transform Relationship

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



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

$F(l,m) = \iint_{\text{aperture}} f(u,v)\exp(2\pi i(ul+vm))\,du\,dv$
$f(u,v) = \iint_{\text{hemisphere}} F(l,m)\exp(-2\pi i(ul+vm))\,dl\,dm$

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

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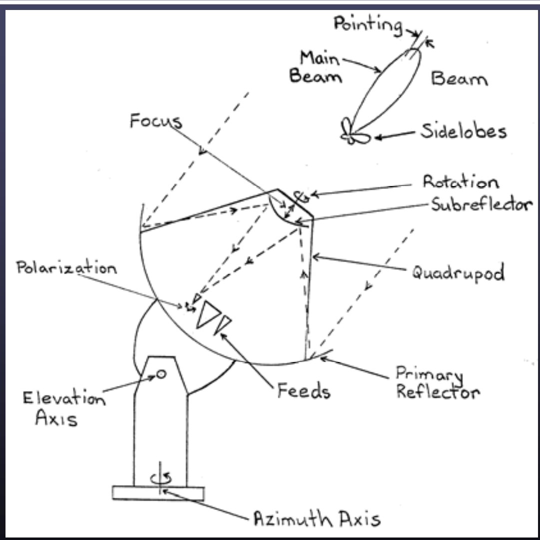
Primary Antenna Key Features



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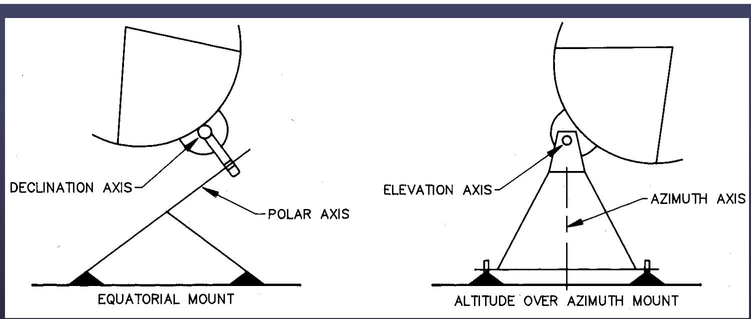
Types of Antenna Mount



Equatorial mount:

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

Altitude over azimuth mount:

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

Beam Rotation on the Sky

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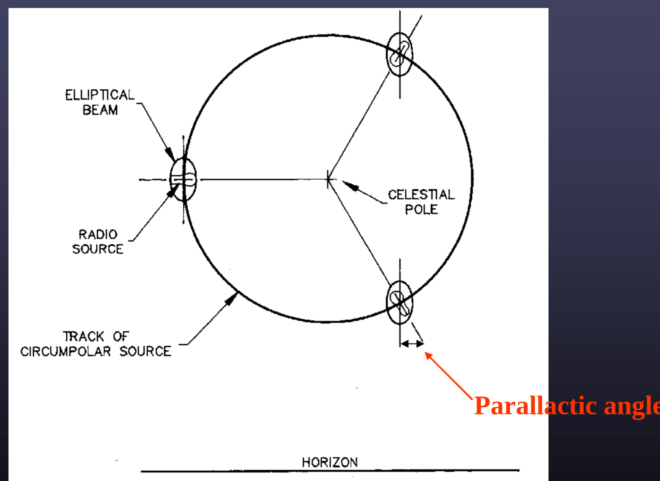

Reflector Types

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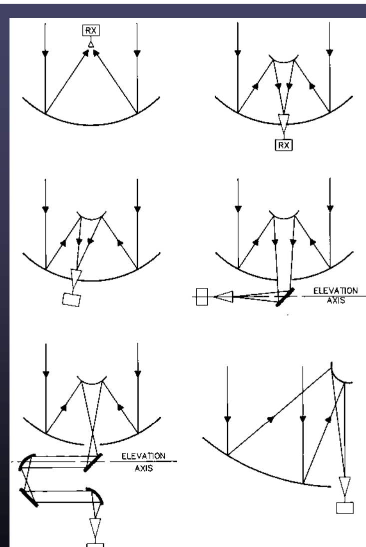
Prime focus (GMRT)

Offset Cassegrain (VLA, VLBA)

Beam Waveguide (NRO)



Cassegrain focus (AT, ALMA)

Naysmith (OVRO)

Dual Offset (ATA, GBT)

Reflector Types

Prime focus
(GMRT)

Cassegrain focus
(AT)

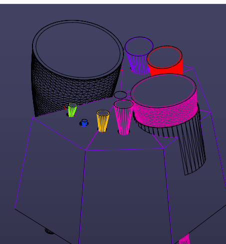
Offset Cassegrain
(VLA)

Naysmith
(OVRO)

Beam Waveguide
(NRO)

Dual Offset
(ATA)

VLA and EVLA Feed System Design



Antenna Performance Parameters

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Aperture Efficiency

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

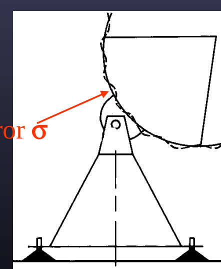
η_{sf} = reflector surface efficiency

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

Antenna Performance Parameters

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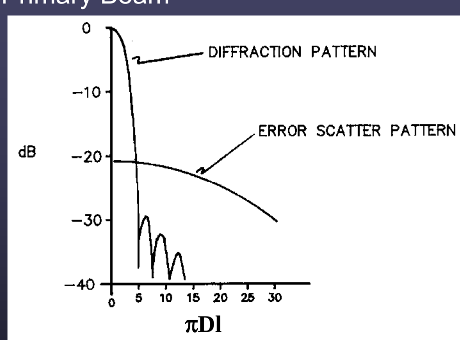
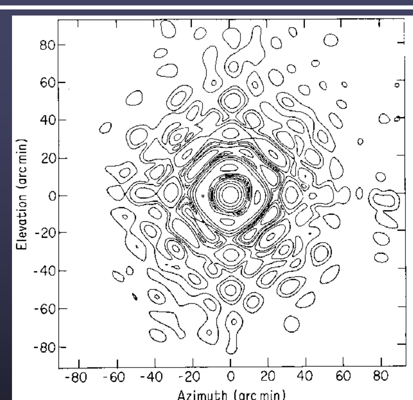
Primary Beam





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

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

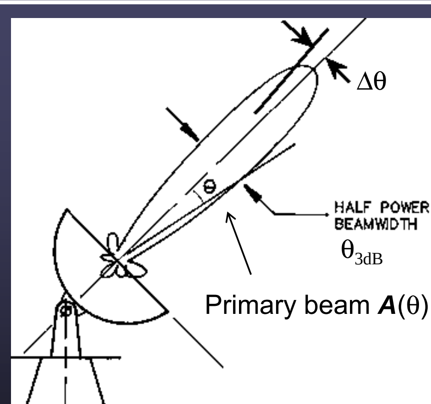
For VLA: θ_{3dB} = 1.02/D, First null = 1.22/D

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 Design

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

Carbon fiber and invar reflector structure

Pointing metrology structure inside alidade

Antenna Performance Parameters

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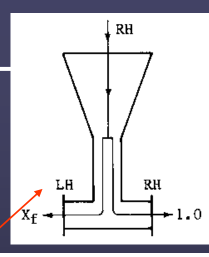
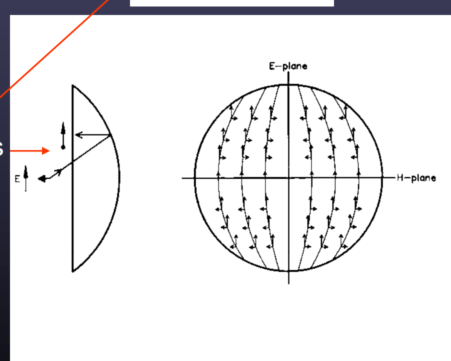


Polarization

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

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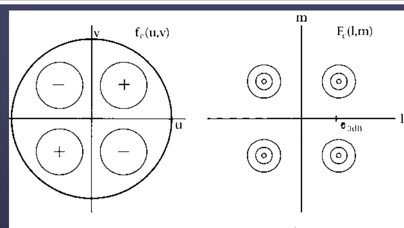
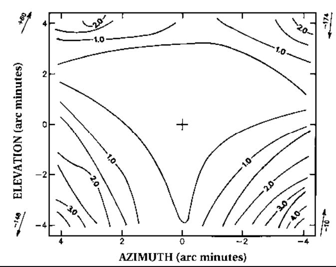
Cross polarized aperture distribution

Cross polarized primary beam



VLA 4.8 GHz cross polarized primary beam



Antenna Holography

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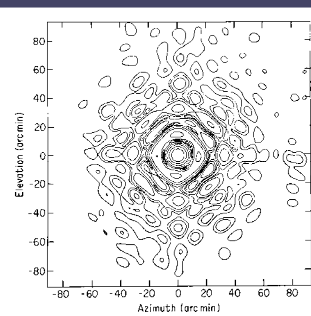
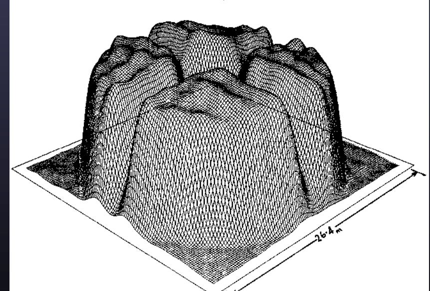
VLA 4.8 GHz

Far field pattern amplitude
Phase not shown



Aperture field distribution amplitude.
Phase not shown



Receivers

Noise Temperature

Matched load
Temp T (°K)

$P_{out} = G * P_{in}$

Rayleigh-Jeans approximation

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

k_B = Boltzman's constant ($1.38*10^{-23}$ J/°K)

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

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

Receivers (cont)

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

SEFD = system equivalent flux density

SEFD = Tsys/K (Jy)

EVLA 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

Corrections to Chapter 3 of Synthesis Imaging in Radio Astronomy II

Equation 3-8: replace u,v with l,m

Figure 3-7: abscissa title should be πDl