Antennas and Receivers in Radio Astronomy

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Outline

- Context
- Types of antennas
- Antenna fundamentals
- Reflector antennas
  - Mounts
  - Optics
- Antenna performance
  - Aperture efficiency
  - Pointing
  - Polarization
- Receivers

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.

VLA @ 4.8 GHz (C-band)

Interferometer Block Diagram

Antenna

Front End

IF

Back End

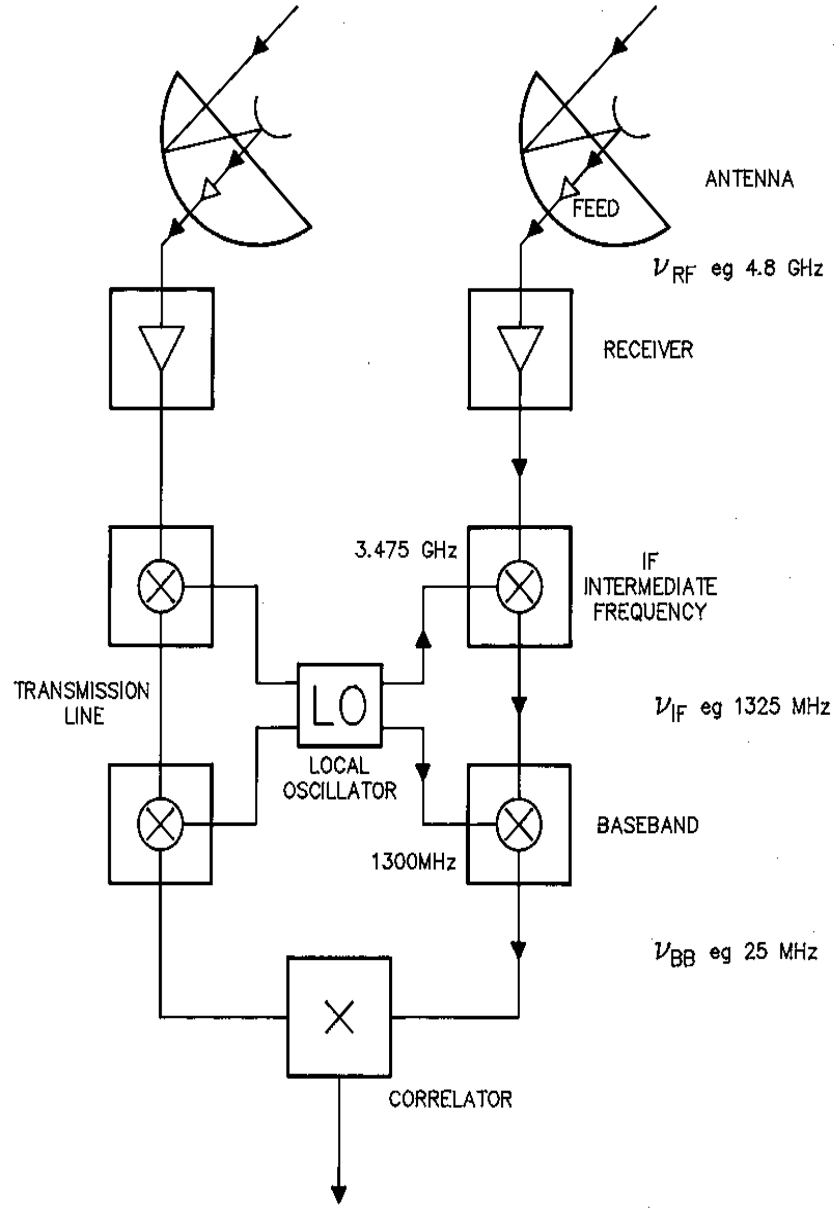
Correlator

Key

Amplifier

Mixer

Correlator

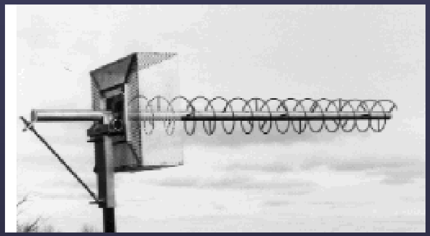


Types of Antennas

- Wire antennas $(\lambda > 1\mathrm{m})$
  - Dipole
  - Yagi
  - Helix
  - Small arrays of the above
- Reflector antennas $(\lambda < 1\mathrm{m})$
- Hybrid antennas $(\lambda \approx 1\mathrm{m})$
  - Wire reflectors
  - Reflectors with dipole feeds

Yagi

Helix



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)

$\boldsymbol{A}(\nu,\theta,\phi) = A(\nu,\theta,\phi)/A_0$

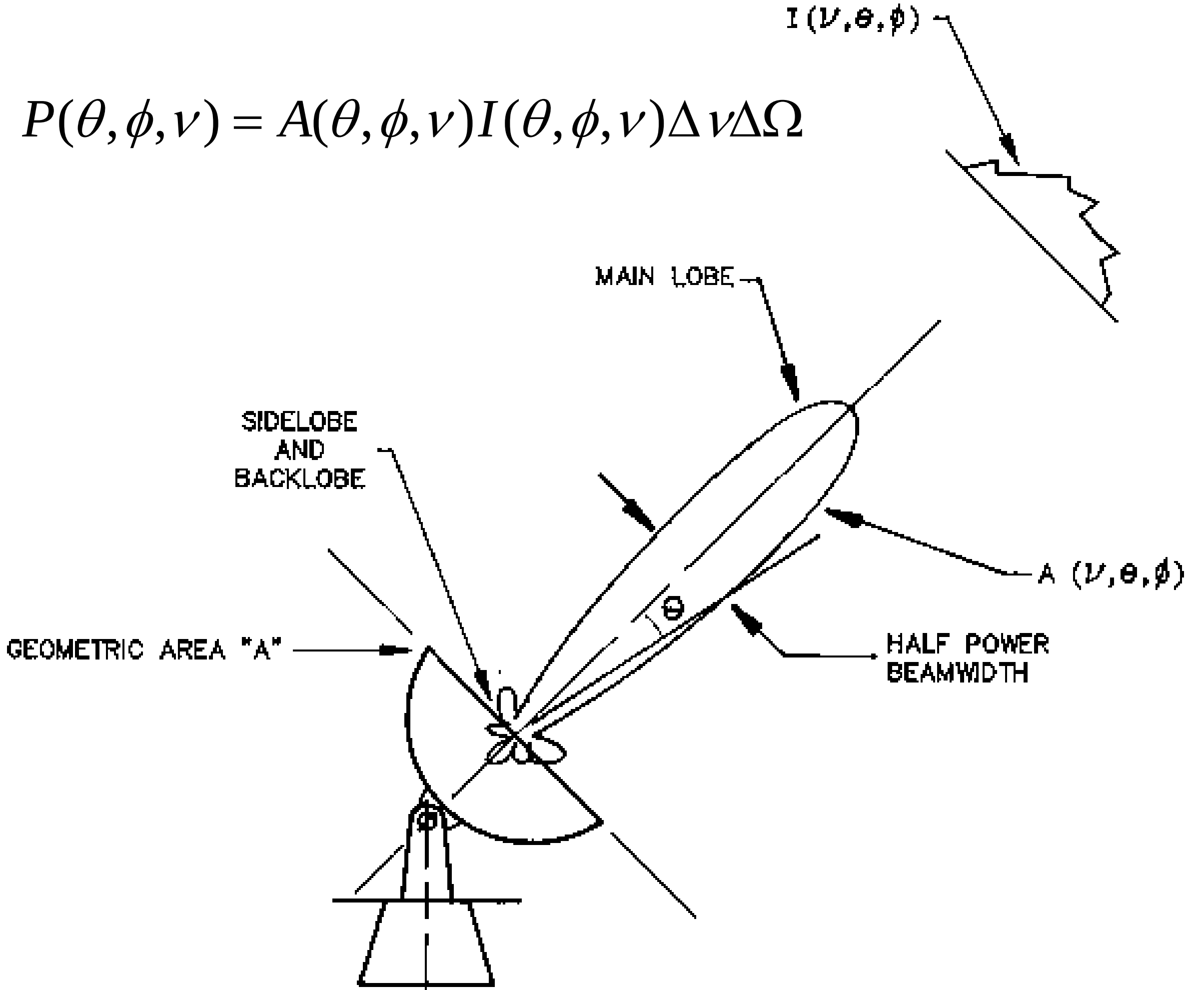
Beam solid angle

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

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

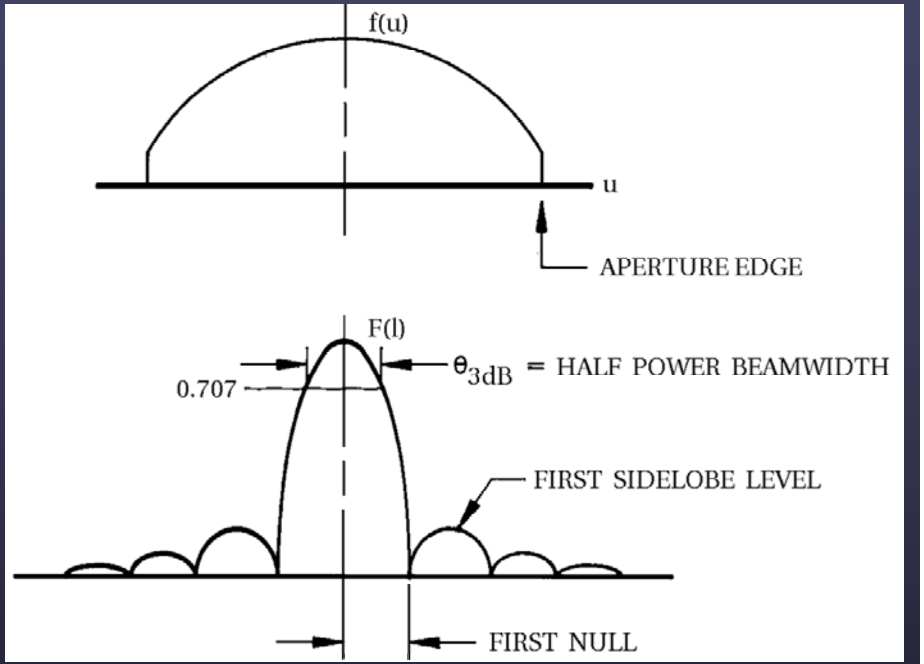
λ = wavelength, ν = frequency

$$P(\theta,\phi,\nu) = A(\theta,\phi,\nu) I(\theta,\phi,\nu) \Delta\nu \Delta\Omega$$



Aperture-Beam Fourier Transform Relationship

What determines the beam shape?



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

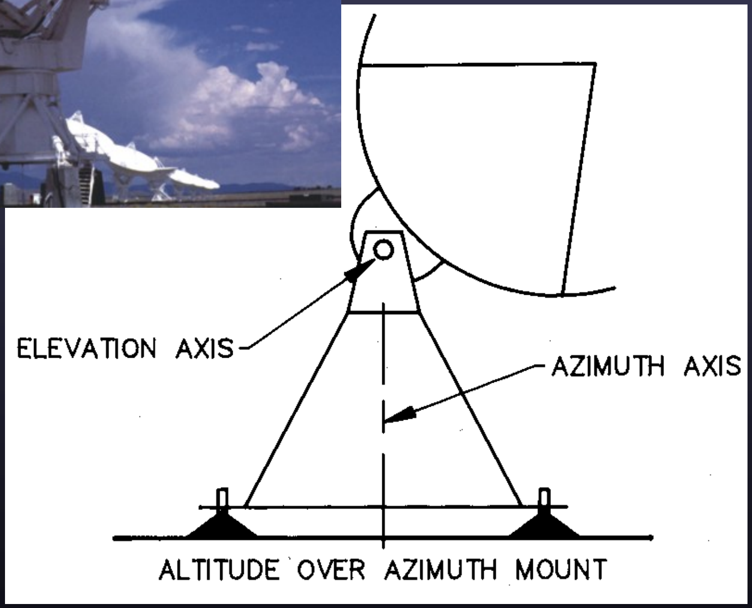
F(l,m) = complex far-field voltage pattern
$l = \sin\theta\cos\phi$, $m = \sin\theta\sin\phi$

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

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

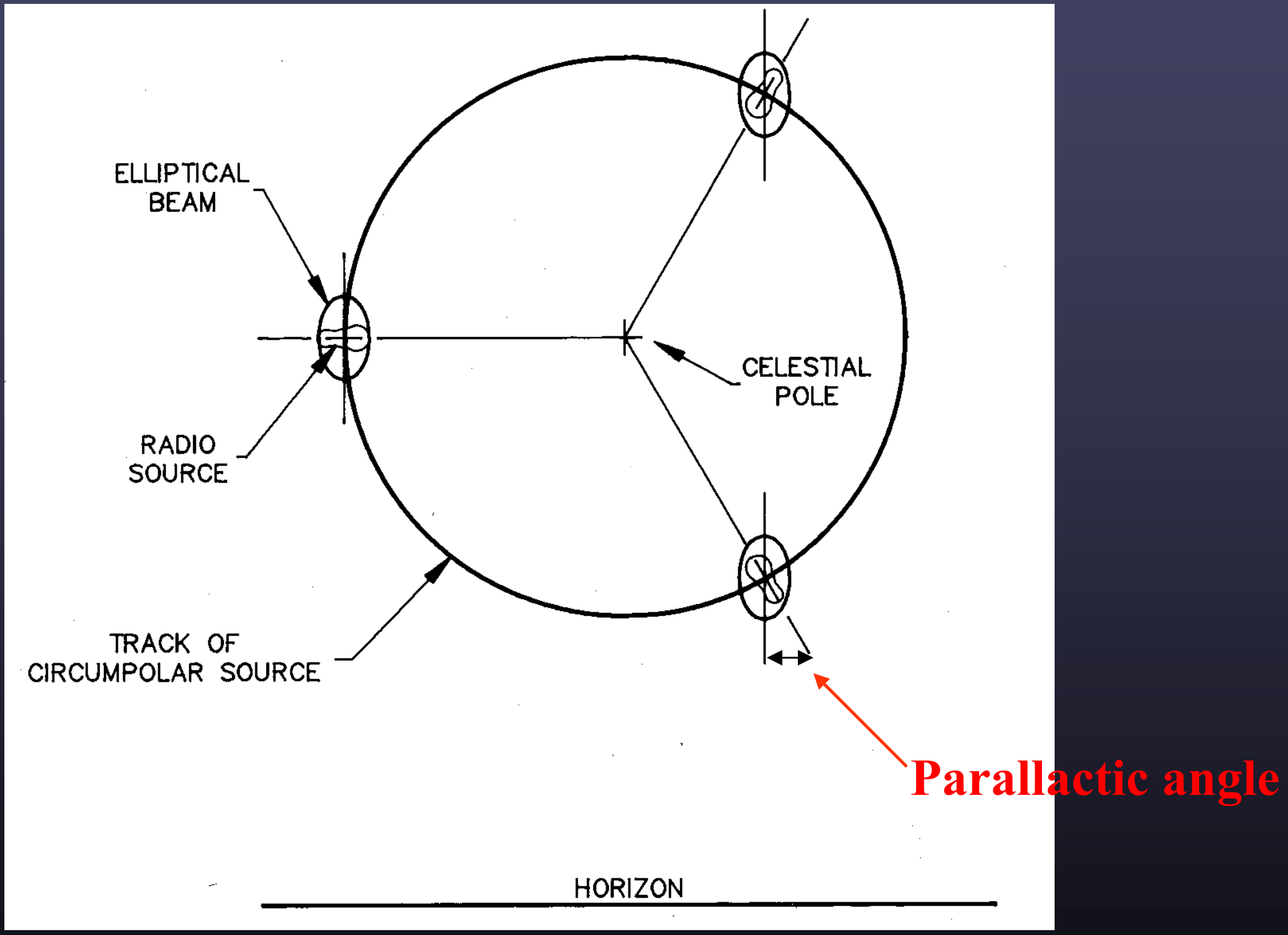
For VLA: θ_{3dB} = 1.02/D, First null = 1.22/D,
D = reflector diameter in wavelengths

Antenna Mounts: Altitude over Azimuth



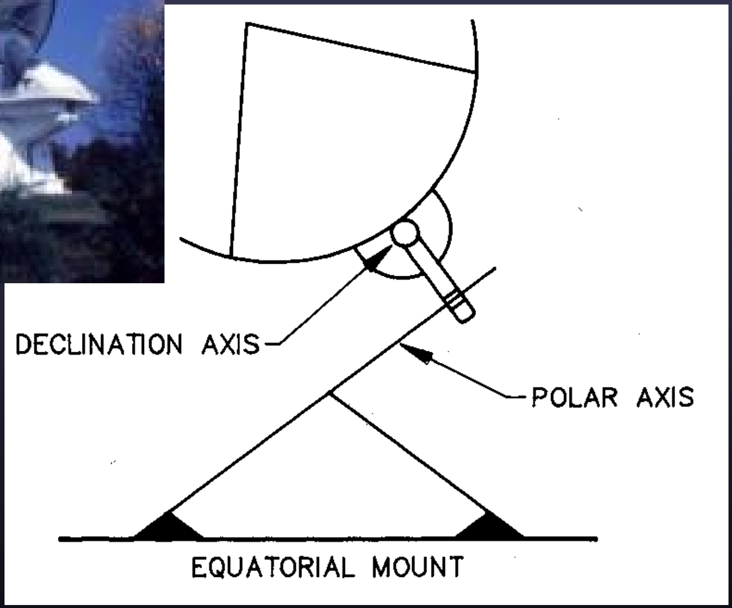
- Advantages
  - Cost
  - Gravity performance
- Disadvantages
  - Zone of avoidance
  - Beam rotates on sky

Beam Rotation on the Sky



Antenna Mounts: Equatorial

- Advantages
  - Tracking accuracy
  - Beam doesn't rotate
- Disadvantages
  - Cost
  - Gravity performance
  - Sources on horizon at pole



Reflector Optics

Prime focus

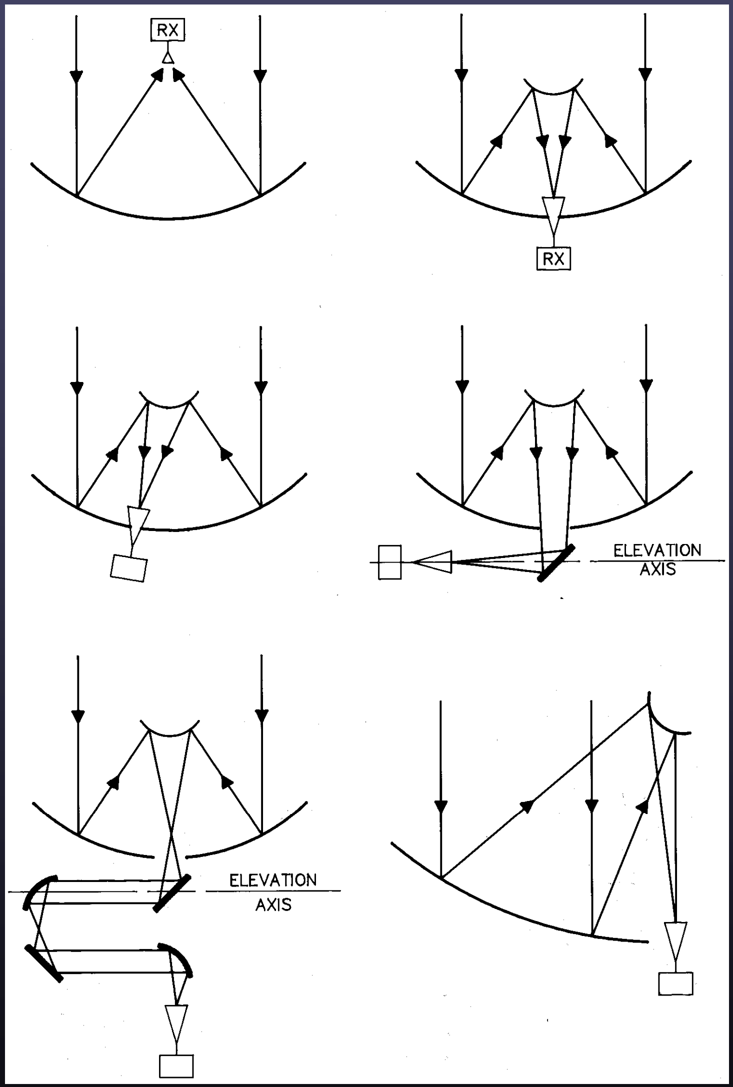
Cassegrain focus

Offset Cassegrain

Naysmith

Beam Waveguide

Dual Offset



Reflector Optics: Limitations

- Prime focus
  - Over-illumination (spillover) can increase system temperature due to ground pick-up
  - Number of receivers, and access to them, is limited
- Subreflector systems
  - Can limit low frequency capability. Feed horn too large.
  - Over-illumination by feed horn can exceed gain of reflector’s diffraction limited sidelobes
    - Strong sources a few degrees away may limit image dynamic range
- Offset optics
  - Support structure of offset feed is complex and expensive

Reflector Optics: Examples

Prime focus
(GMRT)

Cassegrain focus
(AT)

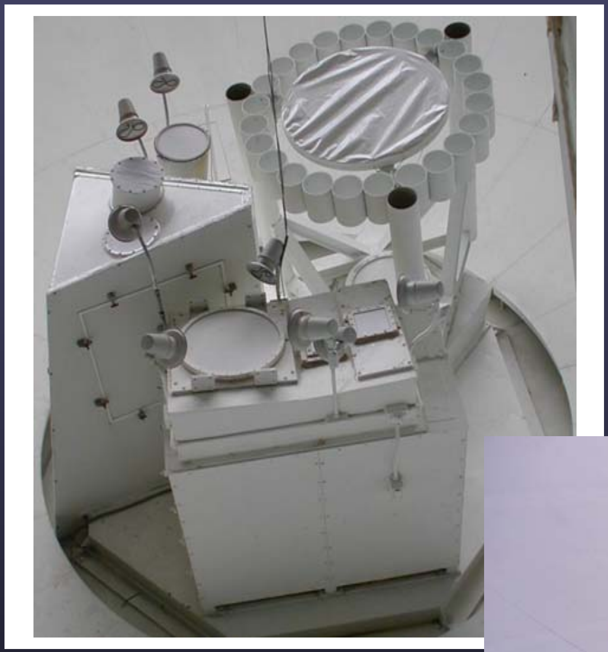
Offset Cassegrain
(VLA)

Naysmith
(OVRO)

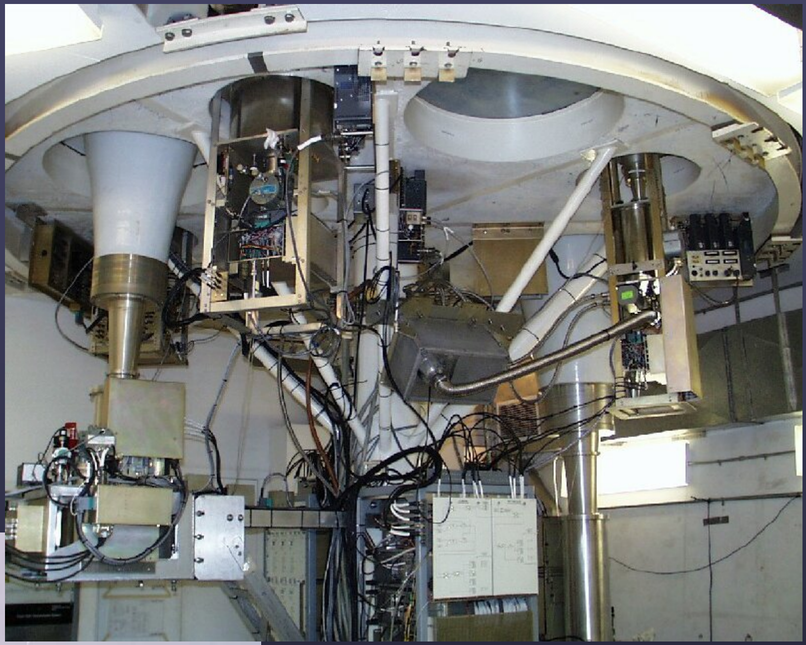
Beam Waveguide
(NRO)

Dual Offset
(GBT)

Feed Systems



VLA



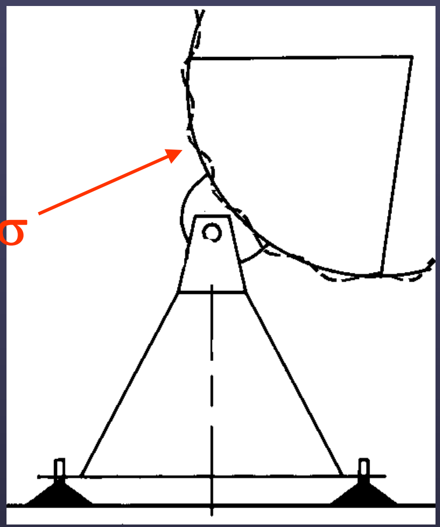
GBT

EVLA

Antenna Performance: Aperture Efficiency

On axis response: $A_0 = \eta A$

Efficiency: $\eta = \eta_{sf} \times \eta_{bl} \times \eta_s \times \eta_t \times \eta_{misc}$



η_{sf} = Reflector surface efficiency

Due to imperfections in reflector surface

$\eta_{sf} = \exp(-(4\pi\sigma/\lambda)^2)$ e.g., $\sigma = \lambda/16$, $\eta_{sf} = 0.5$

η_{bl} = Blockage efficiency

Caused by subreflector and its support structure

η_s = Feed spillover efficiency

Fraction of power radiated by feed intercepted by subreflector

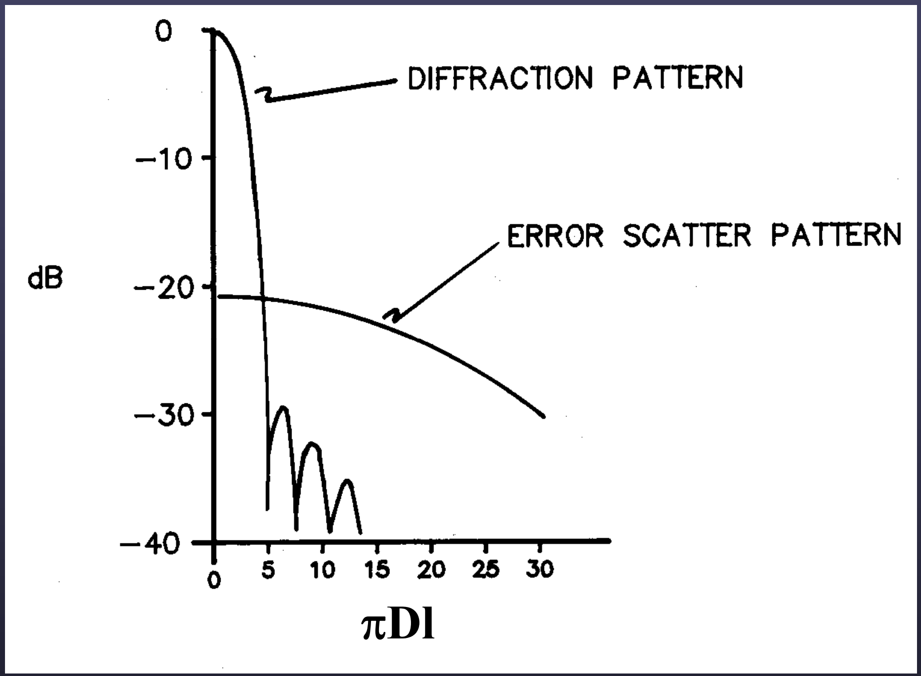
η_t = Feed illumination efficiency

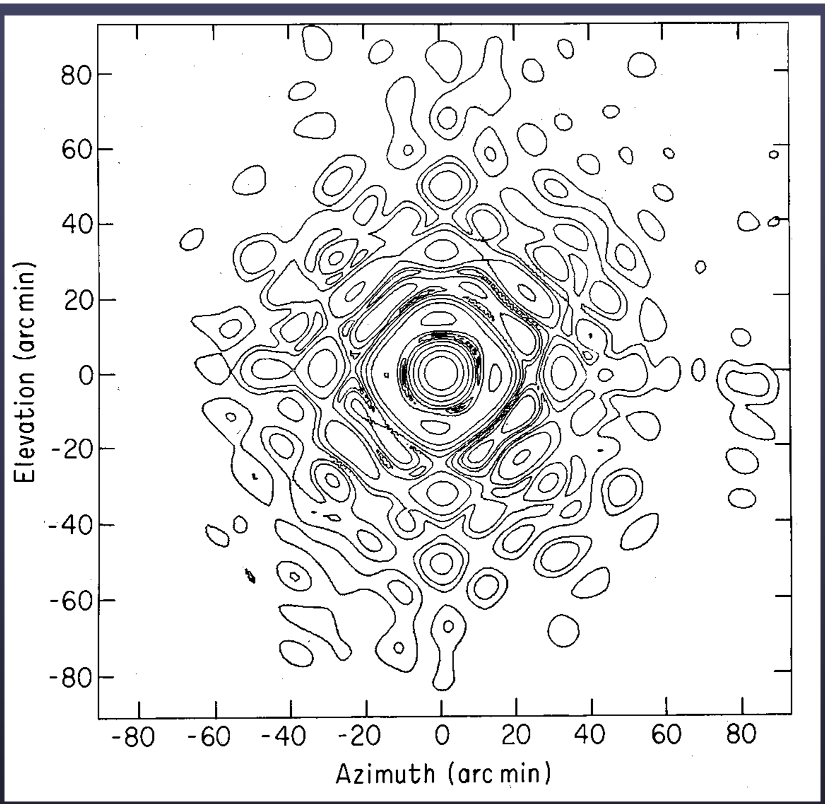
Outer parts of reflector illuminated at lower level than inner part

η_{misc}= Reflector diffraction, feed position phase errors, feed match and loss

Antenna Performance: Aperture Efficiency

Primary Beam





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

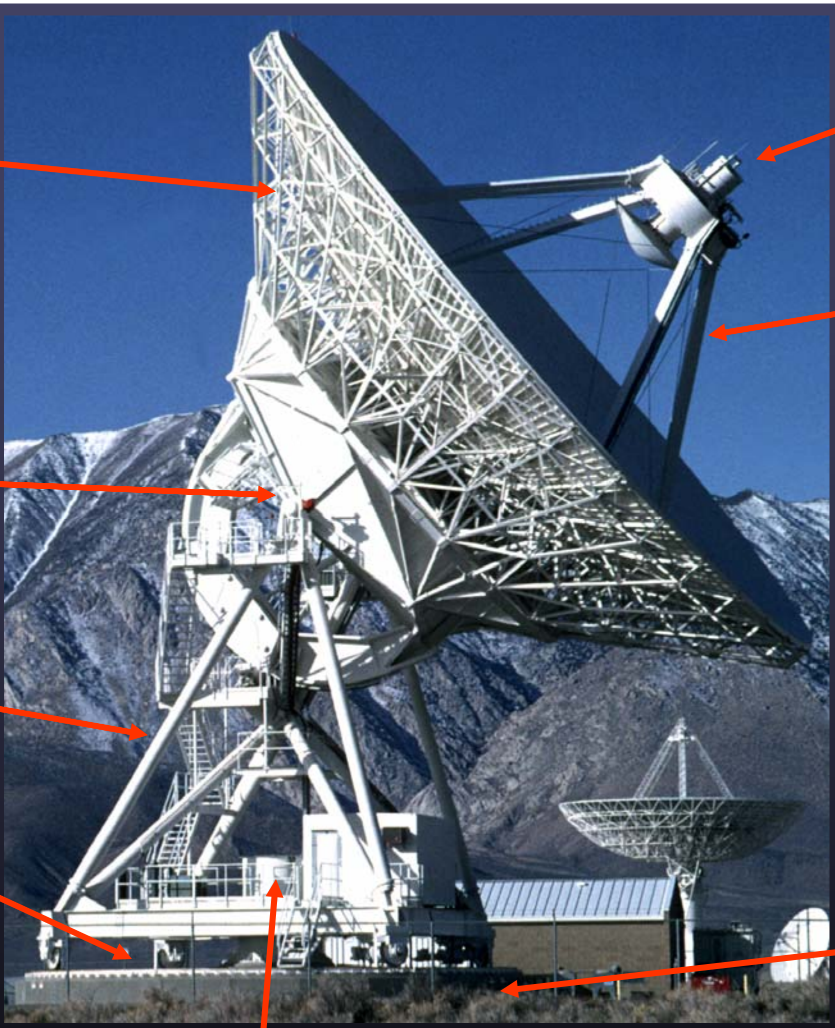
dB = 10log(power ratio) = 20log(voltage ratio)

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

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

Voltage radiation pattern, |F(l,m)|

Antenna Pointing: Practical Considerations



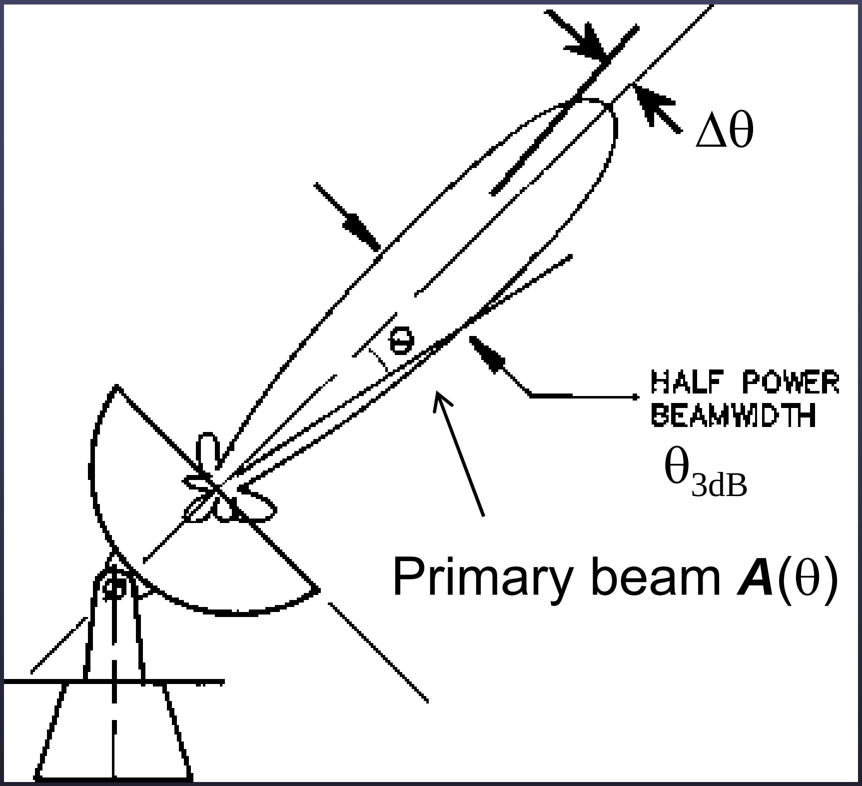
Antenna Performance: Pointing

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

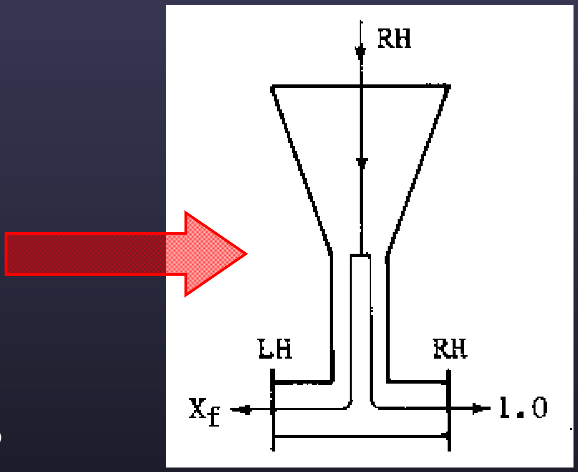


For best VLA pointing use Reference Pointing.
$\Delta\theta$ = 3 arcsec = $\theta_{3dB}/17$ @ 50 GHz

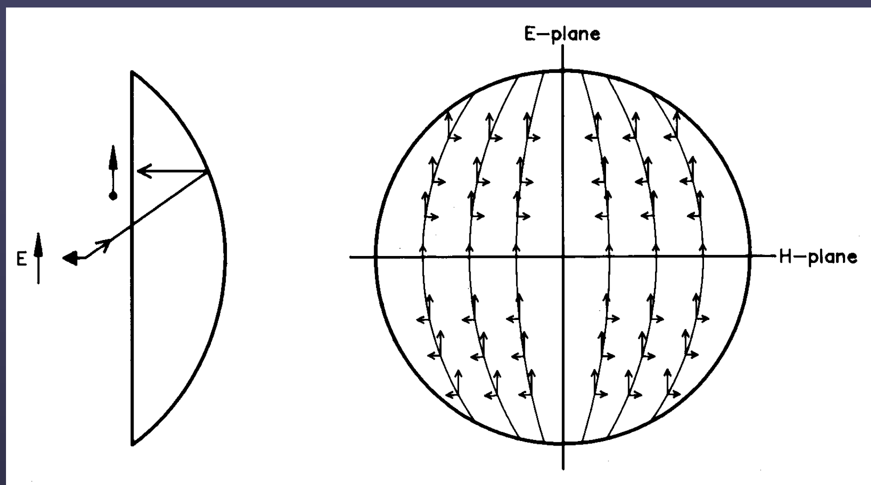
Antenna Performance: Polarization

Antenna can modify the apparent polarization properties of the source:

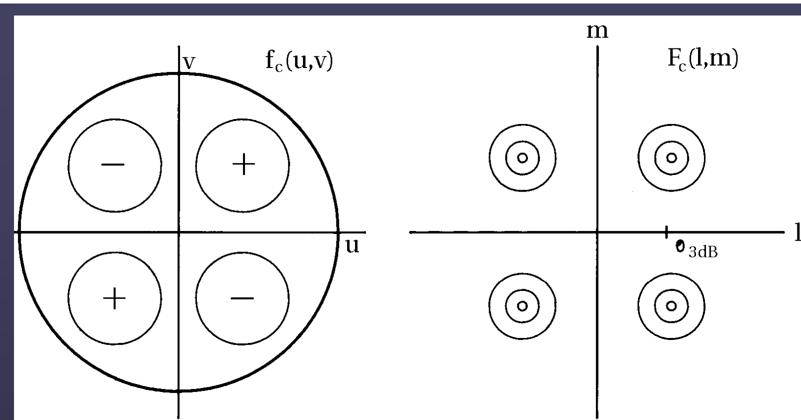
- Antenna structure
  - Symmetry of the optics
  - Reflections in the optics
  - Curvature of the reflectors
- Quality of feed polarization splitter
  - Constant across the beam
- Circularity of feed radiation patterns
  - No instrumental polarization on-axis,
  - But cross-polarization varies across the beam …



Off-Axis Cross Polarization

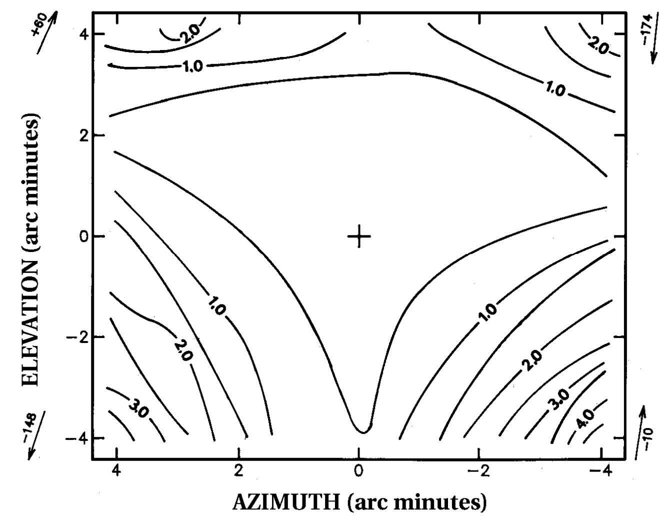


Field distribution in aperture of paraboloid fed by electric dipole



Cross-polarized aperture distribution

Cross-polarized primary beam



VLA 4.8 GHz cross-polarized primary beam

Receivers: Noise Temperature

- Reference received power to the equivalent temperature of a matched load at the input to the receiver
- Rayleigh-Jeans approximation to Planck radiation law for a blackbody

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

Matched load
@ temp T (°K)

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

Receiver

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

Receivers: SEFD

$T_A = \eta AS/(2k_B) = KS$

S = source flux (Jy)

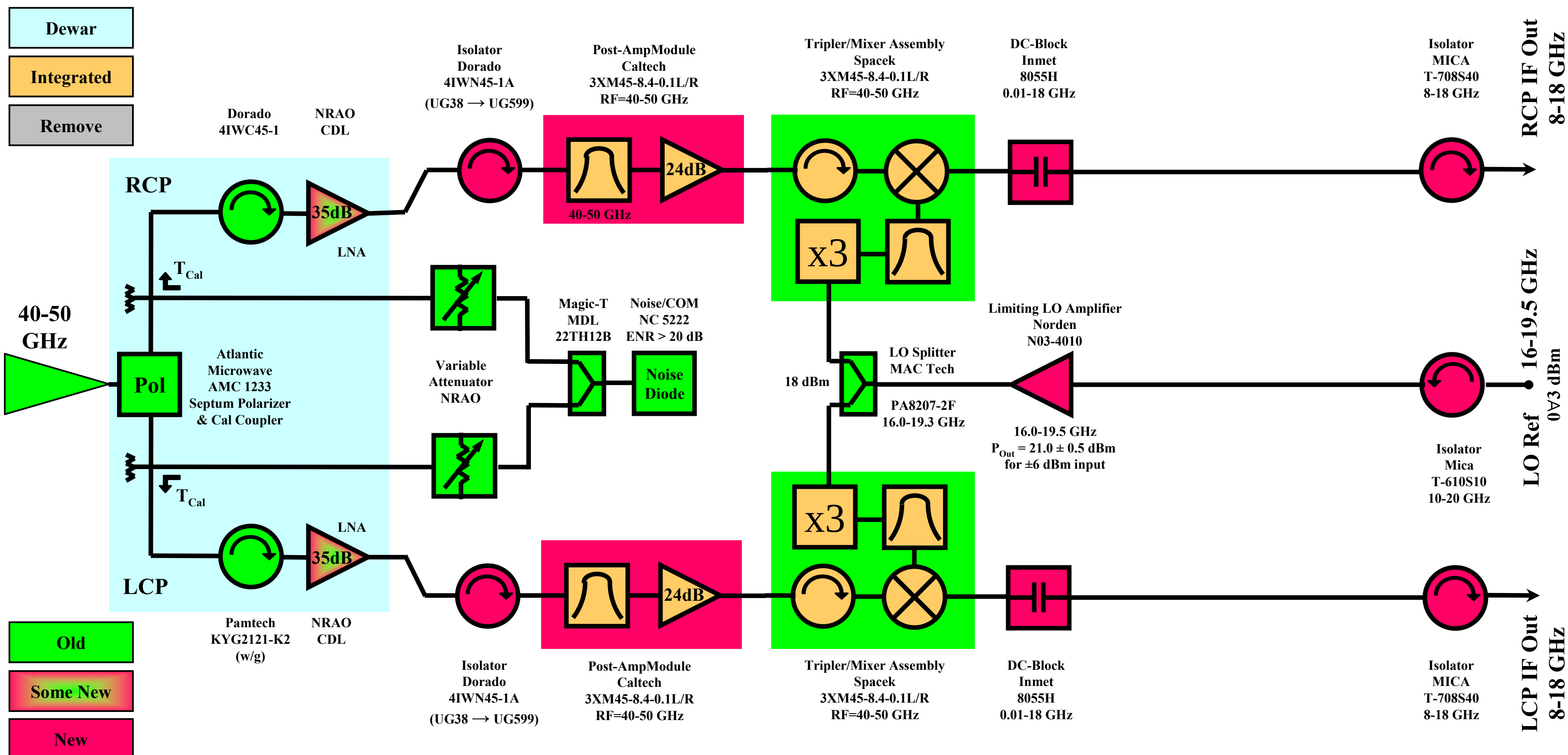
SEFD = system equivalent flux density

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

EVLA Q-Band (40-50 GHz) Receiver



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The University of New Mexico

New Mexico Consortium's
IAS
Institute for Advanced Studies at Los Alamos National Laboratory

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