# Antennas & Receivers in Radio Astronomy

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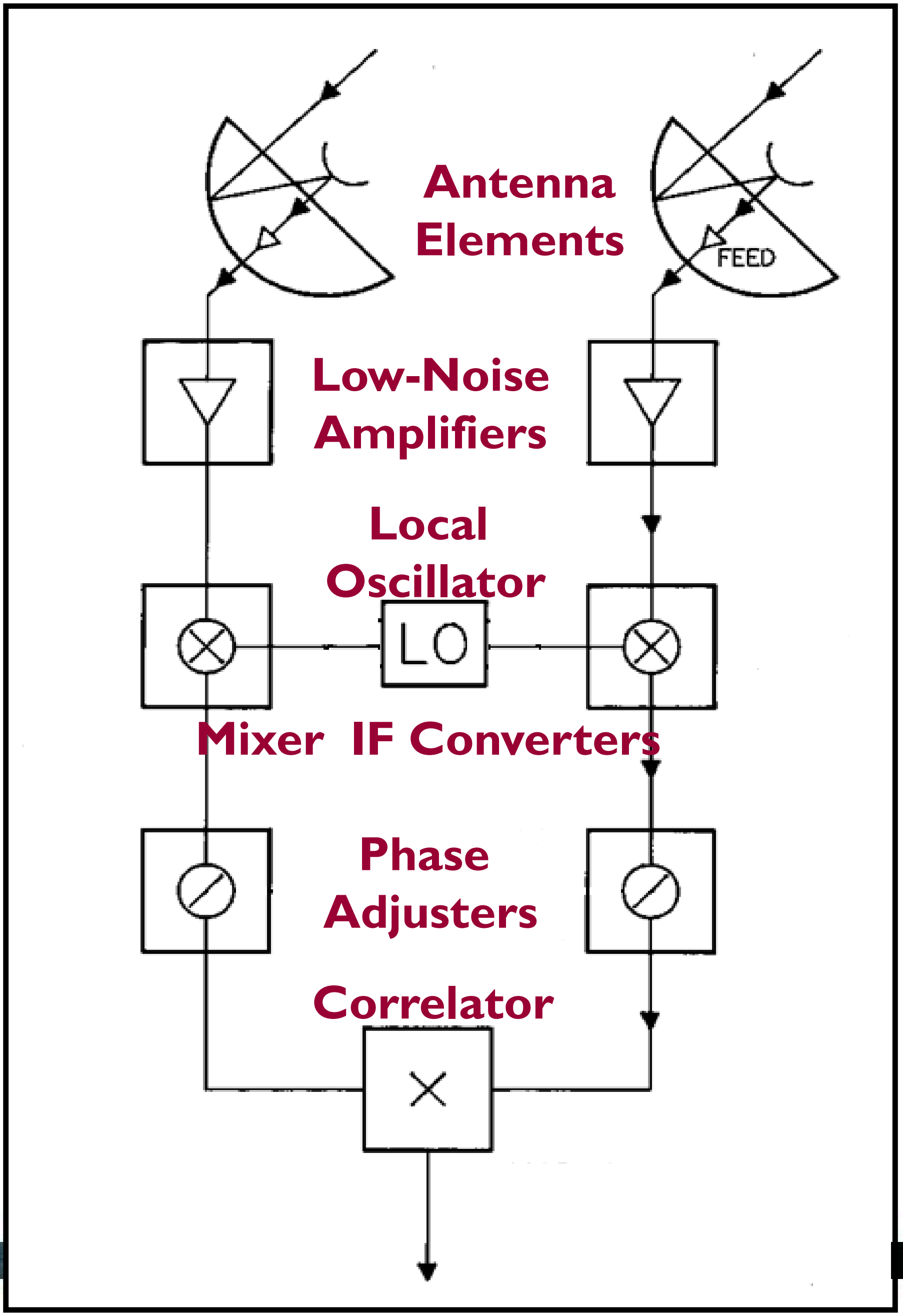
# Purpose & Outline

- Purpose: describe how antenna elements can affect the quality of images produced by an aperture synthesis array
- Scope/Context
- Antennas
  - Fundamentals (antenna types and terminology)
  - Reflector antenna mounts and optics
  - Aperture efficiency
  - Pointing
  - Polarization
- Receivers and Noise Temperature

# Interferometer Block Diagram

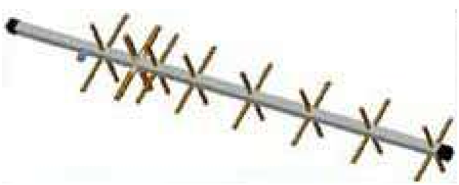


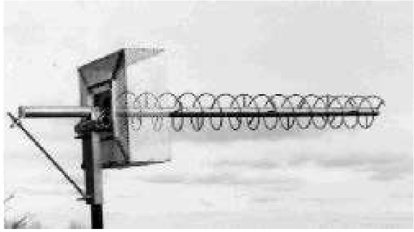
# Effects of Antenna Properties on Data

- 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 can 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.

# Antenna Types

- Purpose of an antenna: capture radiation from an object and couple it to a receiver for detection, digitization, and analysis
- Wire antennas $(\lambda > 1\mathrm{m})$
  - Dipole, Yagi, Helix, or small arrays of each type
- Reflector antennas $(\lambda < 1\mathrm{m})$
- Hybrid antennas $(\lambda \approx 1\mathrm{m})$
  - Wire reflectors
  - Reflectors with dipole feeds





# Terminology & Definitions - I



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

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

On-axis response, $A_0 = \eta A$

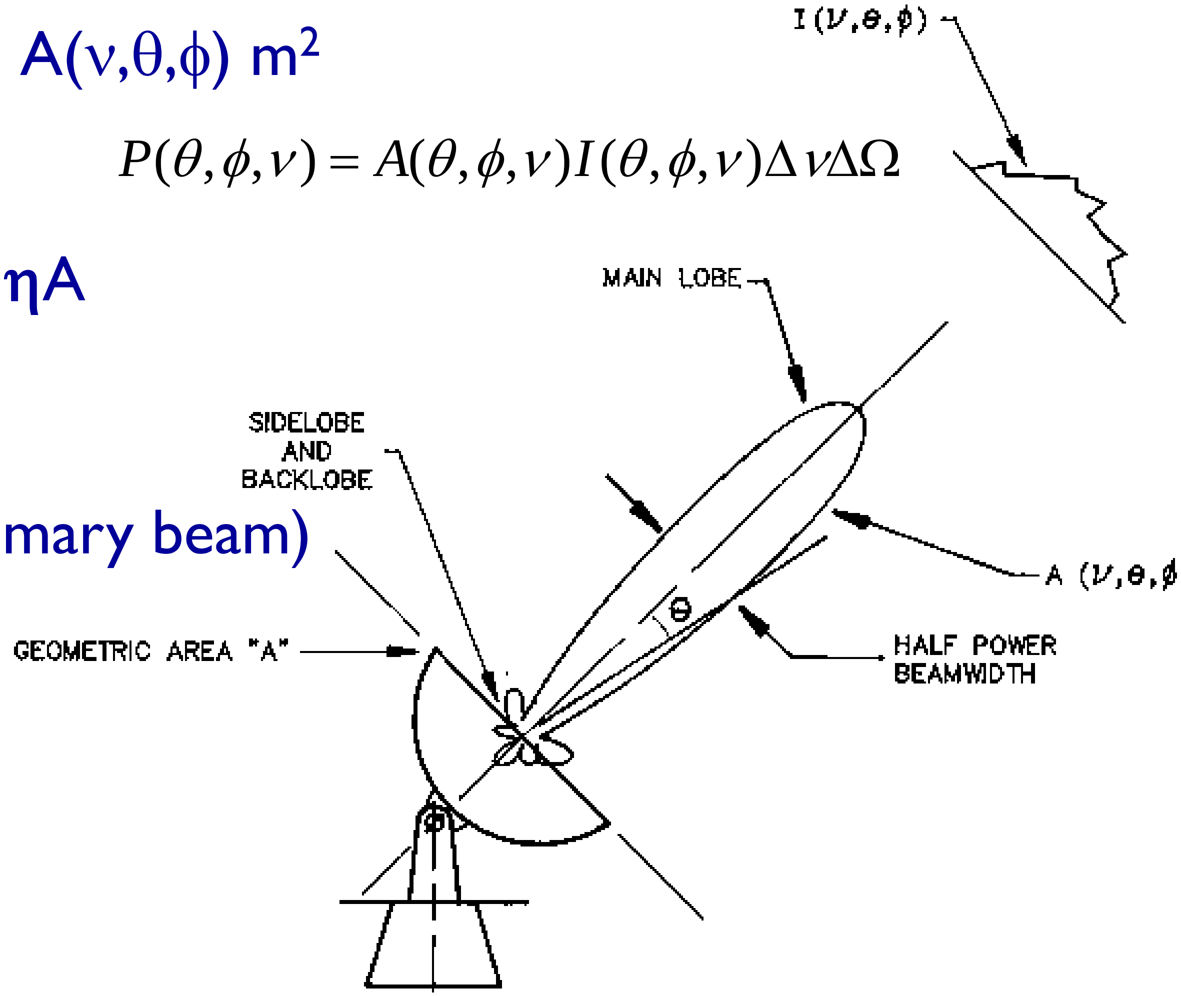
$\eta$ = aperture efficiency

Normalized pattern (primary beam)

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

Beam solid angle

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

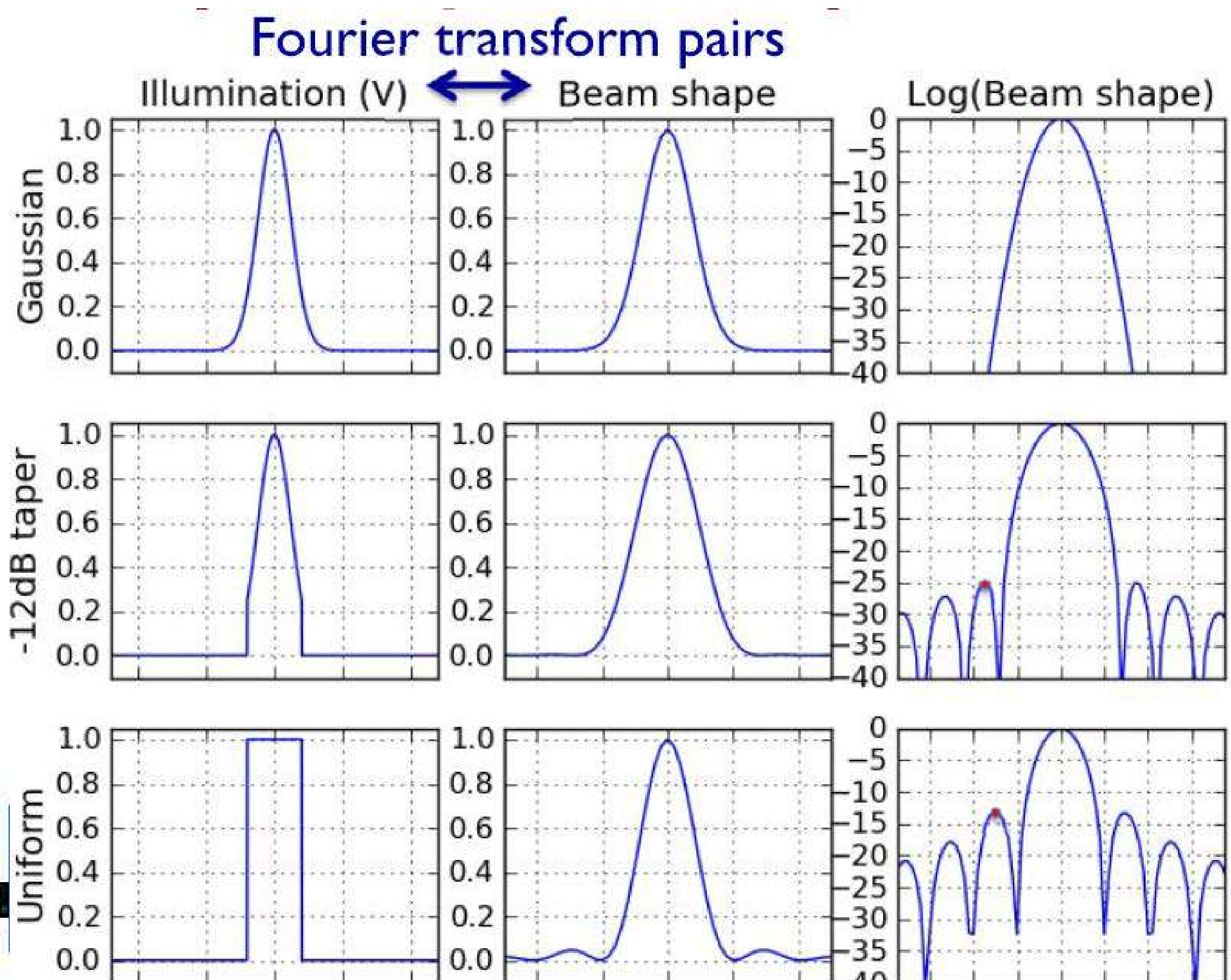


# Terminology & Definitions - II

- $A_0 \, \Omega_A = \lambda^2$ Effective area (gain) & solid angle (field of view)
  - Can have large effective area or large solid angle, but not both at the same time
- Antenna sidelobes and backlobes
  - Increase system temperature due to ground pick up
  - Make antenna susceptible to RFI
  - Sidelobes can limit image dynamic range by detecting strong background sources
- What determines the beam shape? …

# Illumination-Beam Shape Comparisons

Antenna's far-field radiation pattern (*beam*) is related to the Fourier transform of its aperture distribution (*illumination pattern*)

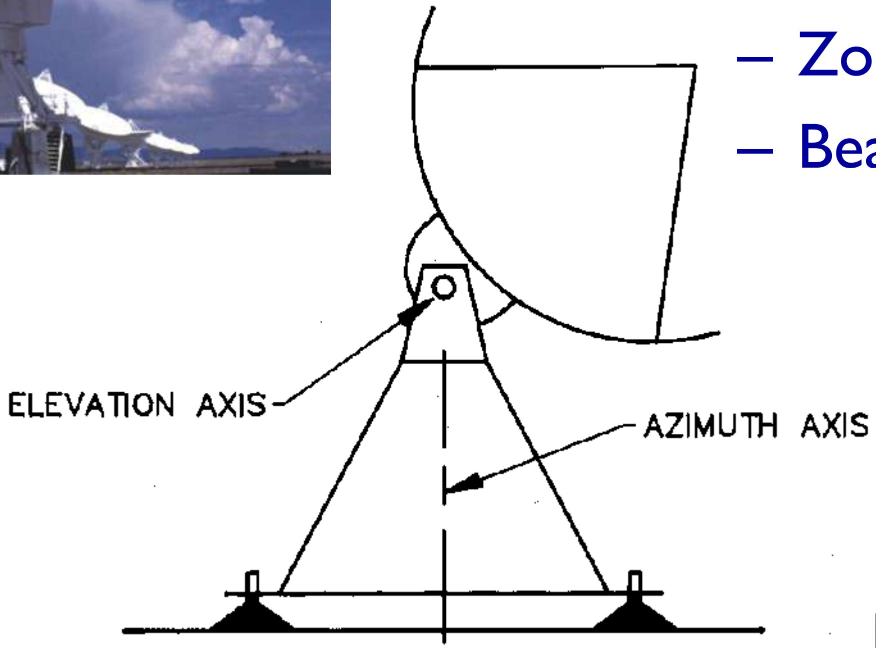



Credit: Hunter

$\theta_{3dB}$ = 1.02/D
First null = 1.22/D
D = diameter in wavelengths

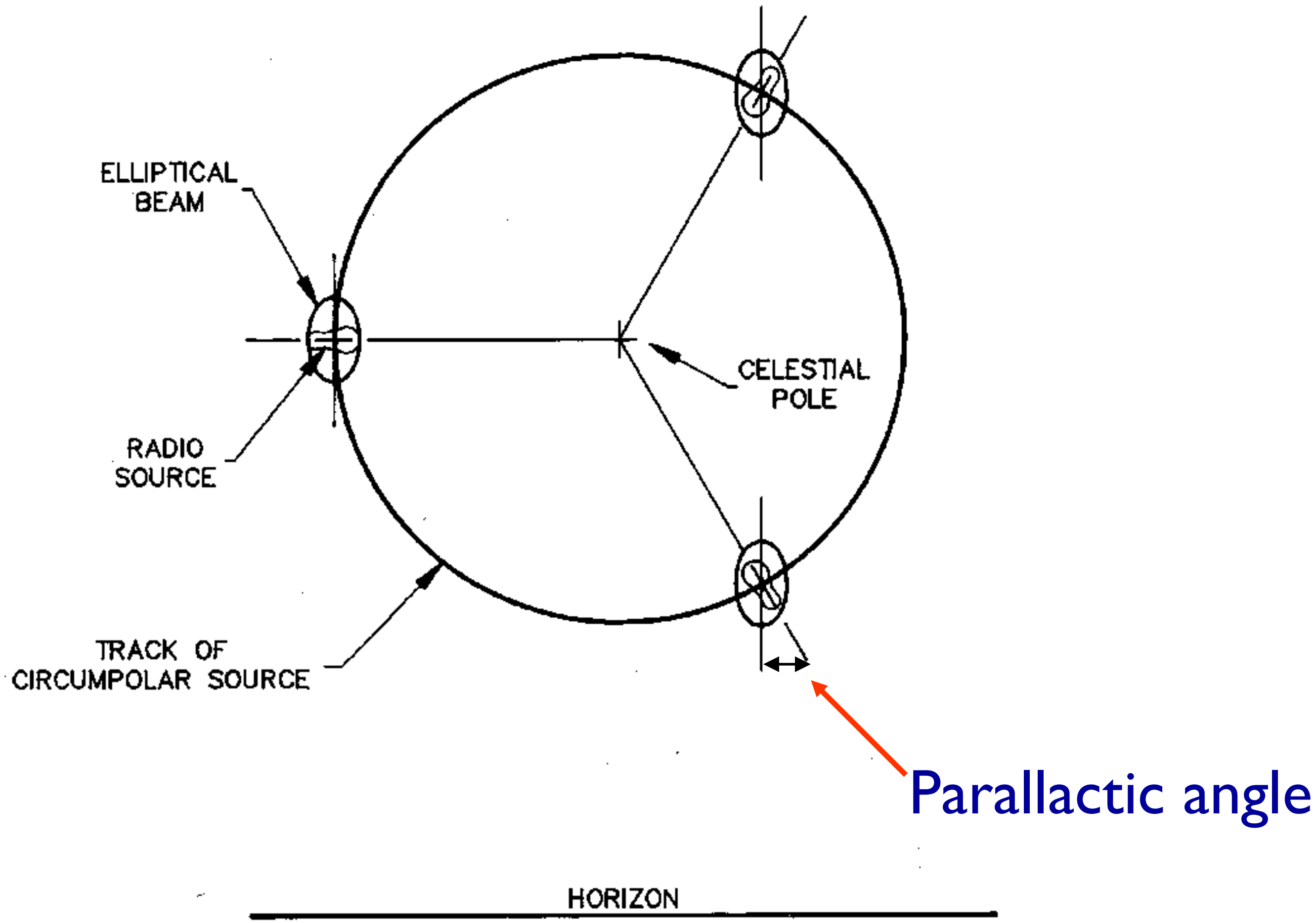
# Antenna Mounts: Altitude over Azimuth

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



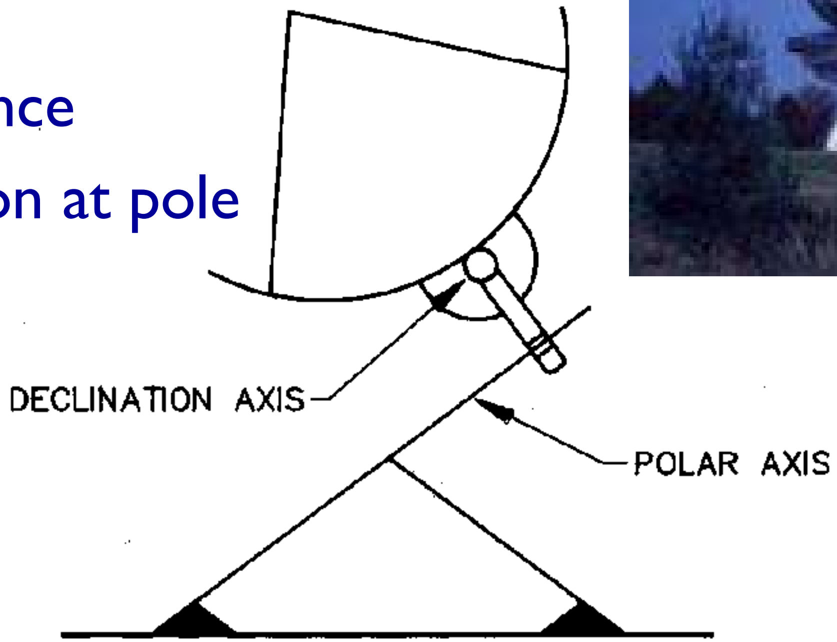

ALTITUDE OVER AZIMUTH MOUNT

# Alt-Az: Beam Rotation on the Sky



# Antenna Mounts: Equatorial

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

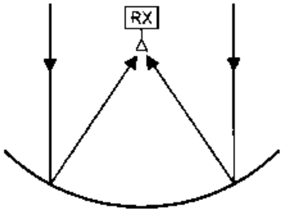


EQUATORIAL MOUNT

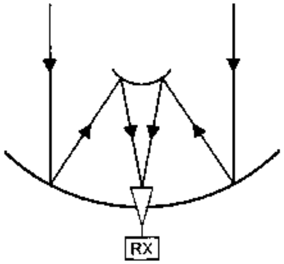
# Antenna Optical Configurations

GMRT

Prime Focus



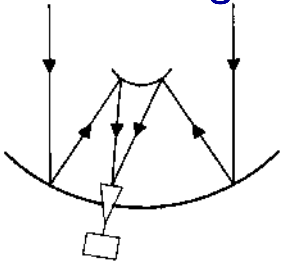

Cassegrain



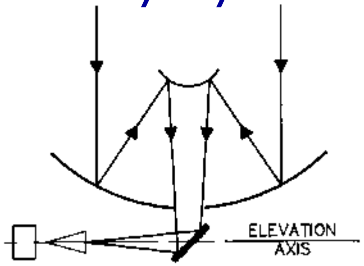

ATCA

VLA

Offset Cassegrain



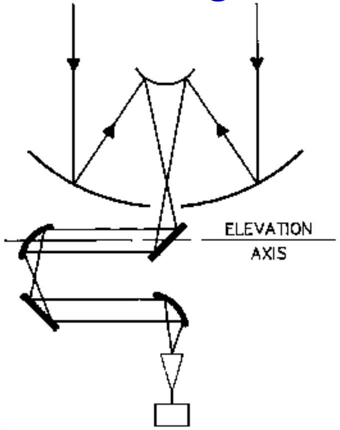
Naysmyth



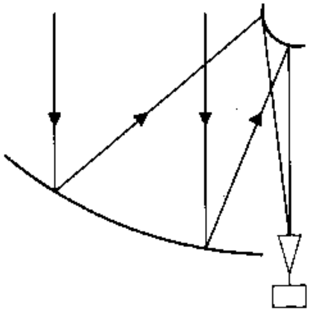

CARMA

NRO

Beam Waveguide



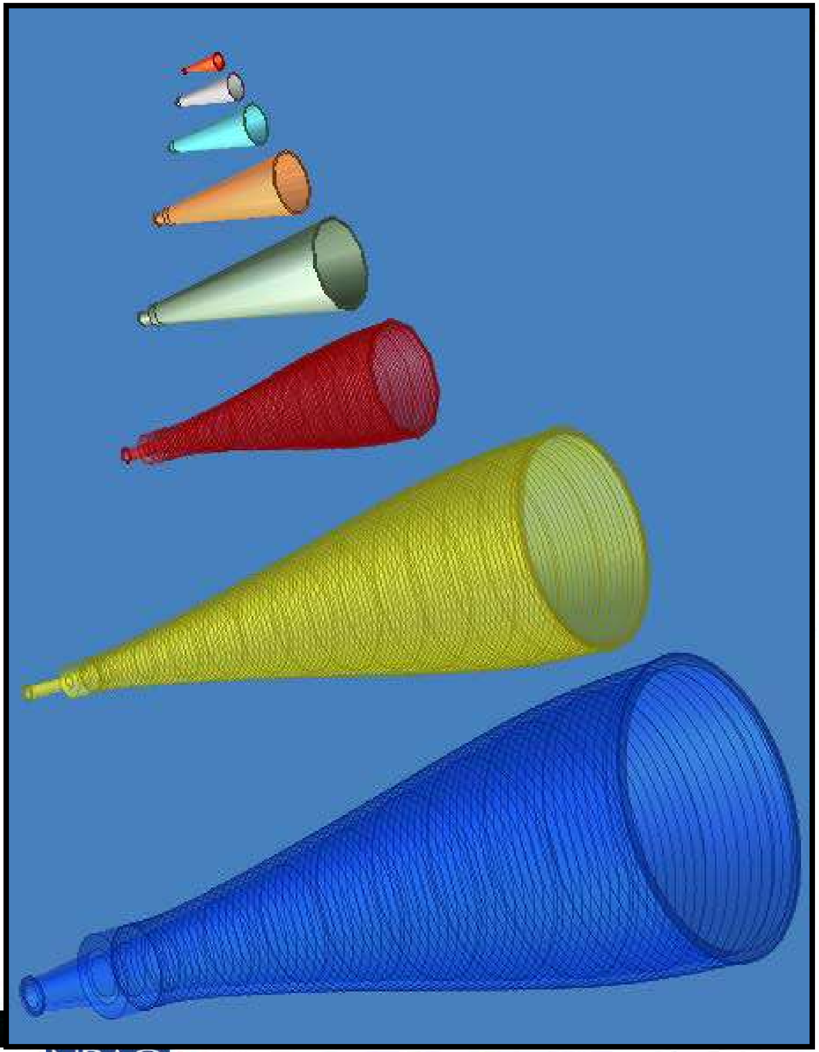

Dual Offset

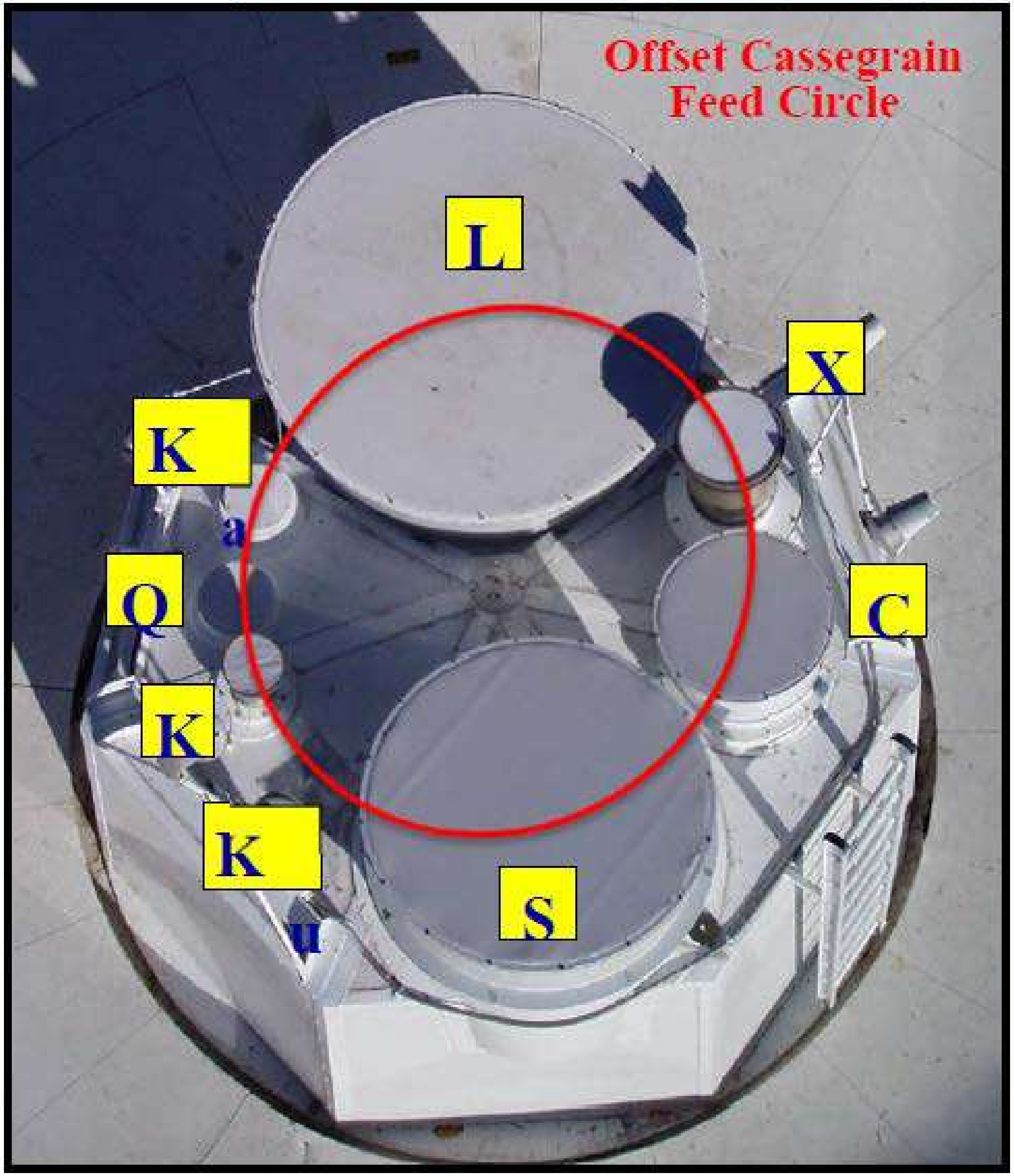


GBT

# JVLA Feed Horns

Credit: Ruff & Hayward





# Optical Configurations, Pros & Cons - I

- Prime Focus
  - Can be used over entire frequency range of the reflector
  - Over-illumination (spillover) can increase system temperature due to ground pick-up
  - Number of receivers and access to them is limited
- Multiple reflector systems
  - More space, easier access to receivers, reduced ground pick-up
  - Any spillover is on cold sky; better for low system noise
  - Can limit low frequency capability. Feed horn too large
  - Over-illumination by feed horn can exceed the gain of the primary reflector's sidelobes
    - Strong sources a few degrees from the antennas' main bean may limit image dynamic range

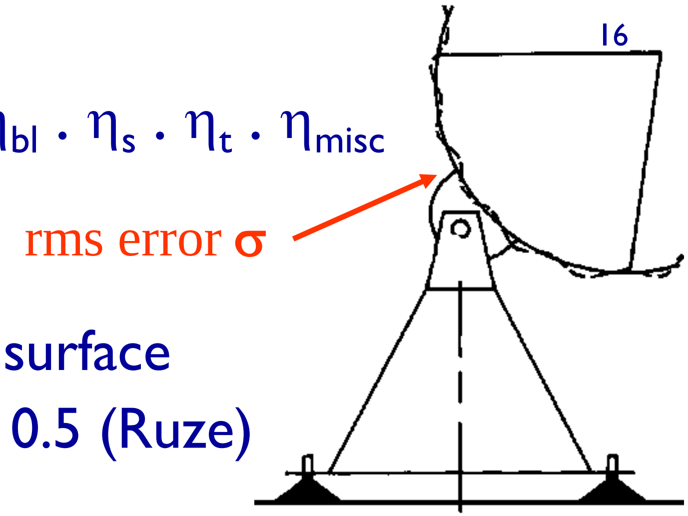
NRAO

# Optical Configurations, Pros & Cons - II

- Offset optics
  - Unblocked aperture:
    - higher aperture efficiency, lower sidelobes
  - Support structure of offset geometry is complex and expensive
  - Expensive panel tooling due to multiple panel sizes

# Aperture Efficiency

On axis response: $A_0 = \eta A$, Efficiency: $\eta = \eta_{sf} \cdot \eta_{bl} \cdot \eta_s \cdot \eta_t \cdot \eta_{misc}$




$\eta_{sf}$ = Reflector surface efficiency

Due to random imperfections in reflector surface

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

$\eta_{bl}$ = Blockage efficiency. Caused by subreflector and its support structure

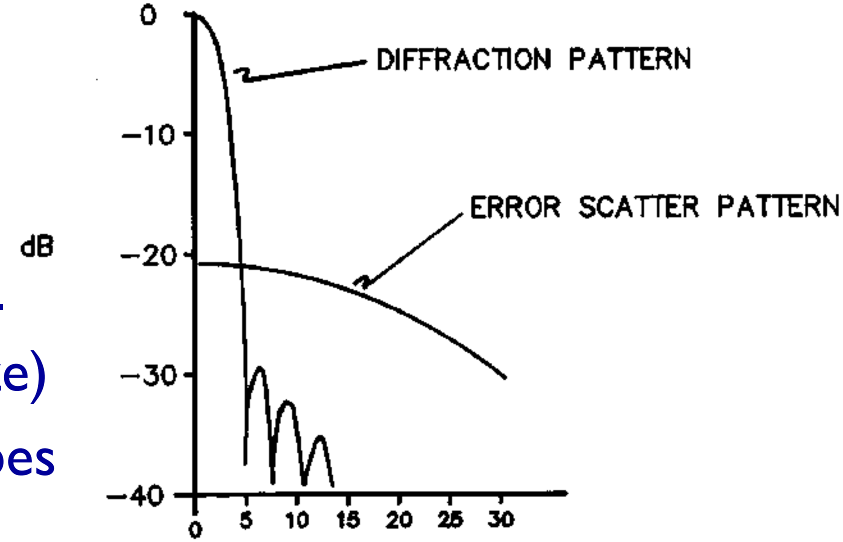
$\eta_s$ = Feed spillover efficiency. Fraction of power radiated by feed intercepted by subreflector

$\eta_t$ = Illumination taper efficiency. Outer parts of reflector illuminated at lower level than inner part

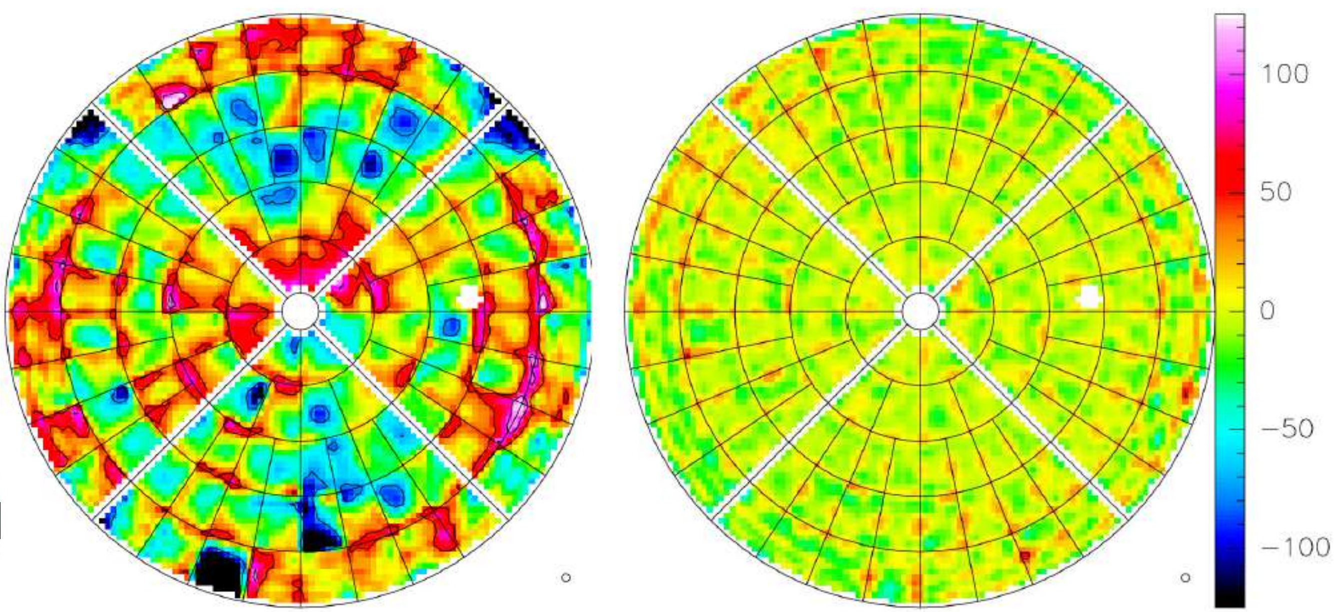
$\eta_{misc}$ = Reflector diffraction, feed position phase errors, feed match and loss

# Surface Errors

- Correlated surface errors can produce an error scatter pattern
  - Pattern width determined by size-scale of correlations (e.g. panel size)
  - Level could exceed that of sidelobes




Before adjustment (43mm) After adjustment (11mm)

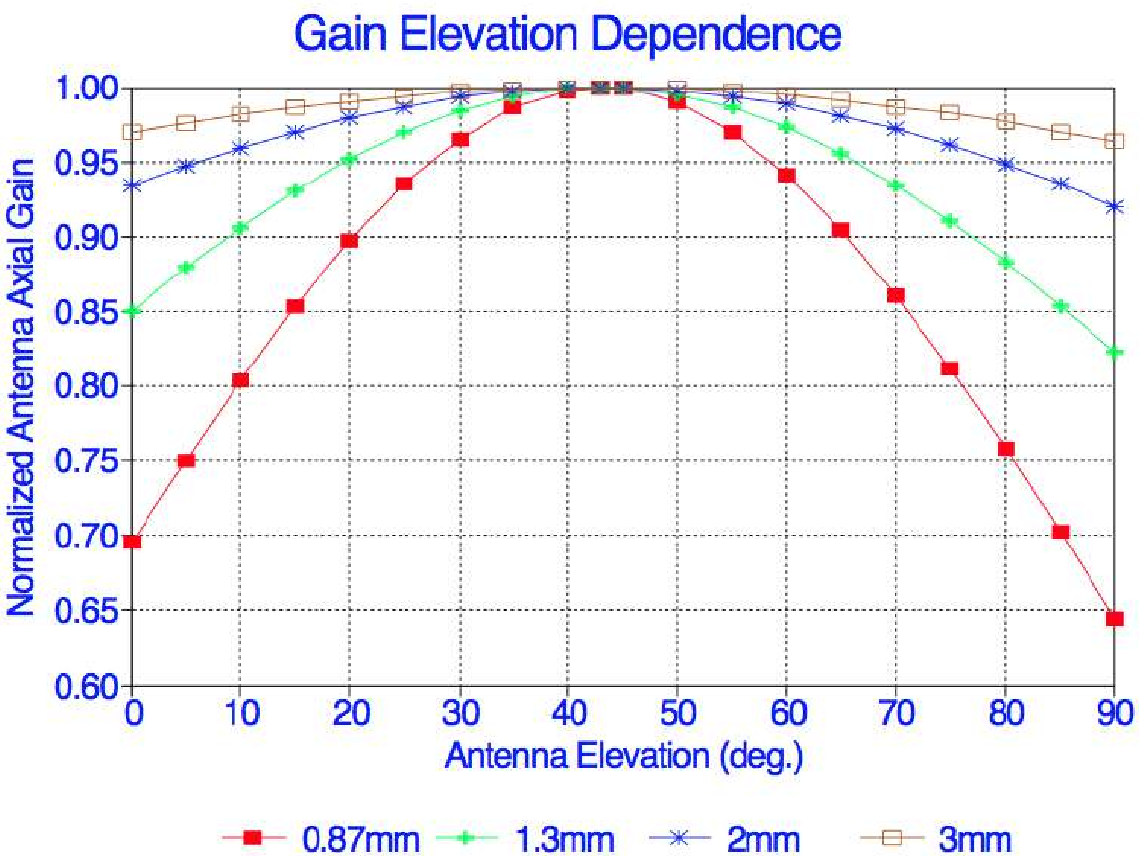



ALMA surface panel adjustment: phase map

# Antenna Gain - I

- Antenna gain (on-axis response) varies with elevation, primarily due to the redistribution of gravitational forces within the antenna backup structure

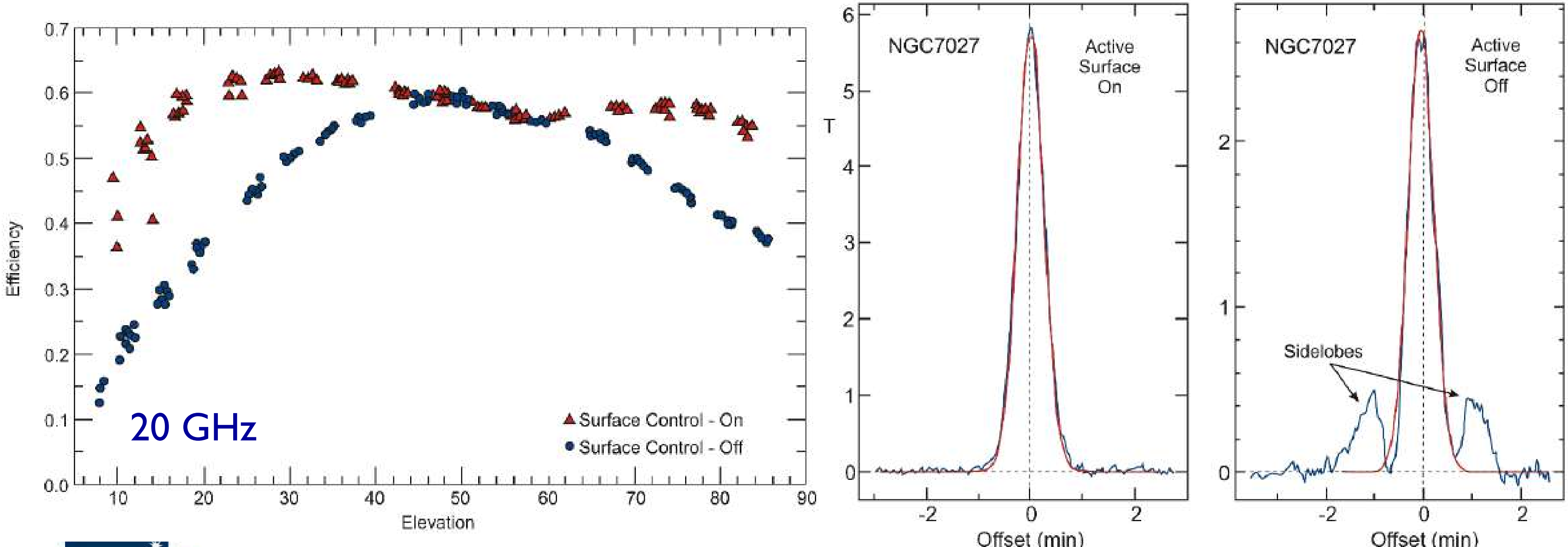
IRAM 30m (predicted, 1999)




credit: Hunter

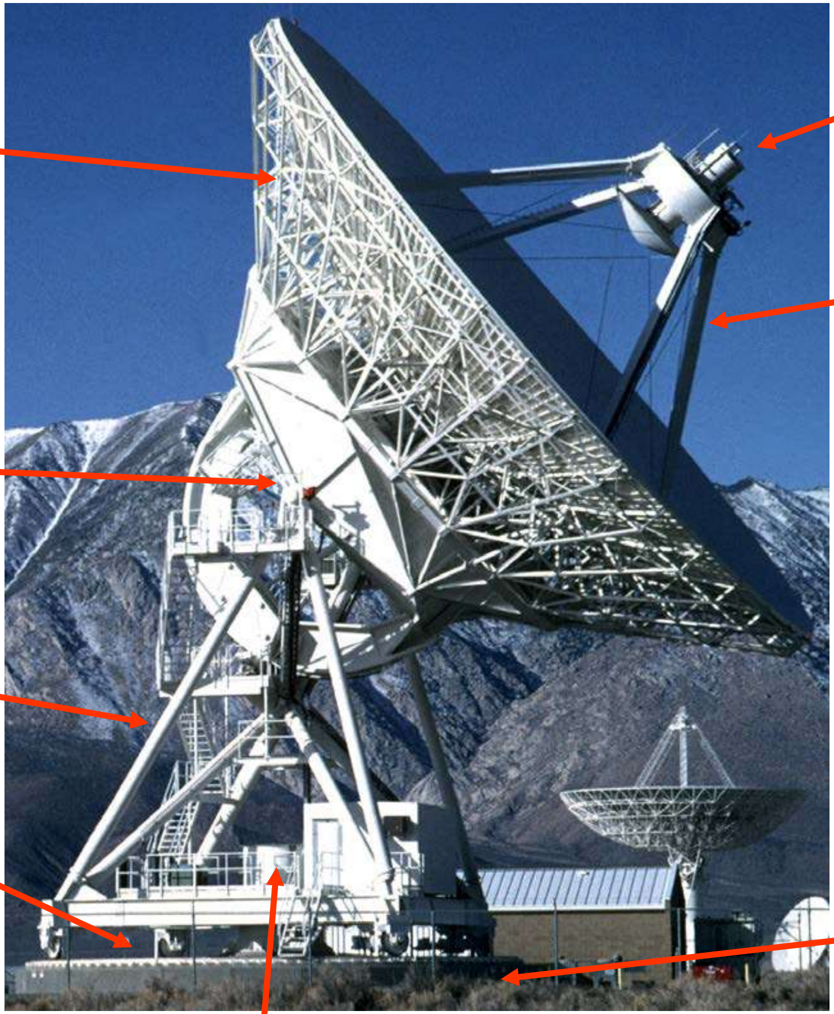
# Antenna Gain - II

- Gravitational distortions and elevation-dependent gain can be compensated with an active surface
- GBT active surface: 2004 surface panels, 2209 surface actuators




Credit: Prestage & Maddalena

# Antenna Pointing: Practical Considerations



Reflector structure

Subreflector mount

Quadrupod

El encoder

Alidade structure

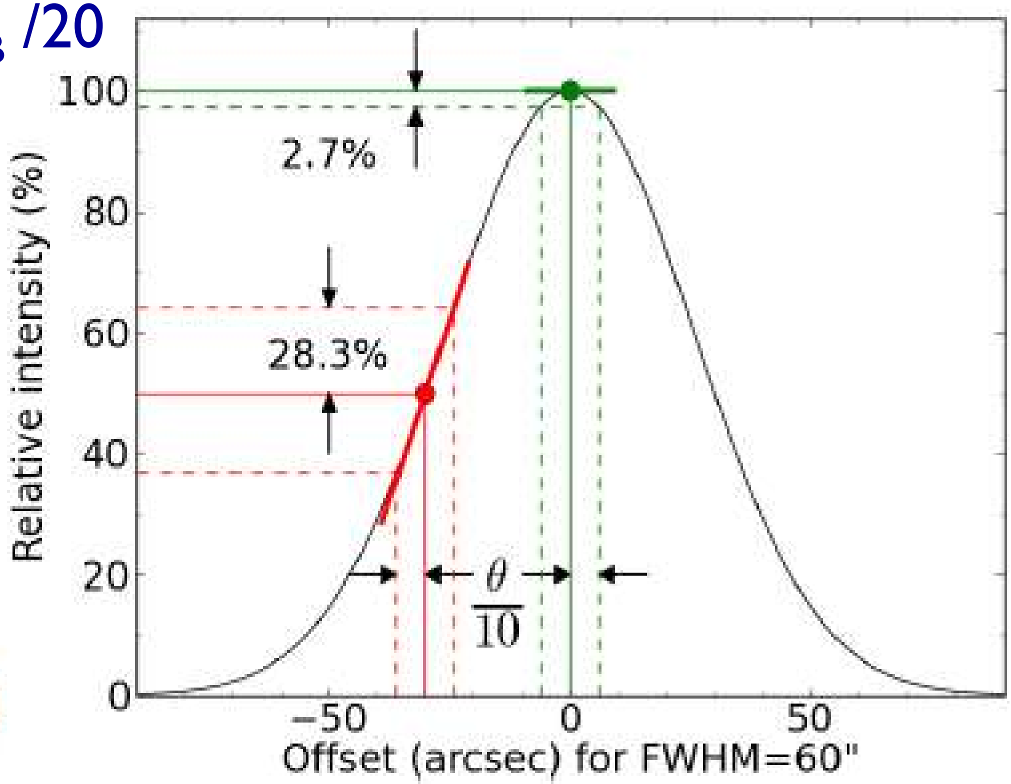
Rail flatness

Foundation

Az encoder

# Antenna Pointing

- "Blind" pointing: ALMA - 2"; VLA - 15"
- Pointing performance can be improved by measuring pointing errors via frequent observations of a nearby calibration source
  - Offset or reference pointing: ALMA – 0.6"; VLA – 3"
- Desired accuracy: $\Delta\theta < \theta_{3dB}/20$
- Large intensity variations at beam edge with $\Delta\theta < \theta_{3dB}/10$




credit: Hunter

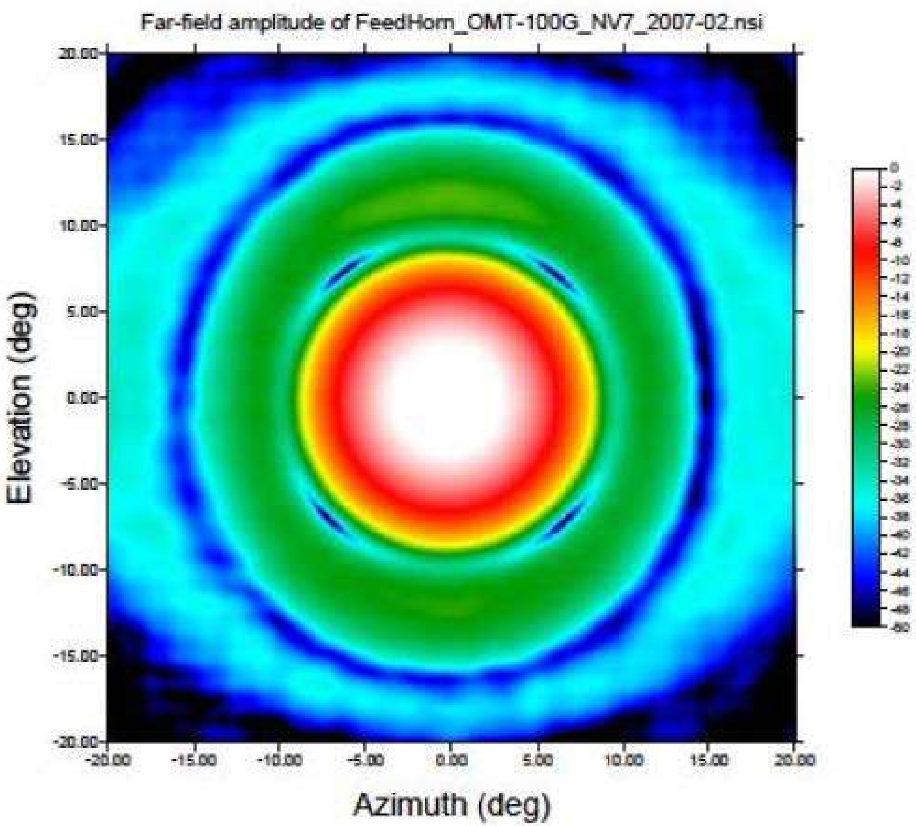
# Antenna Polarization Properties

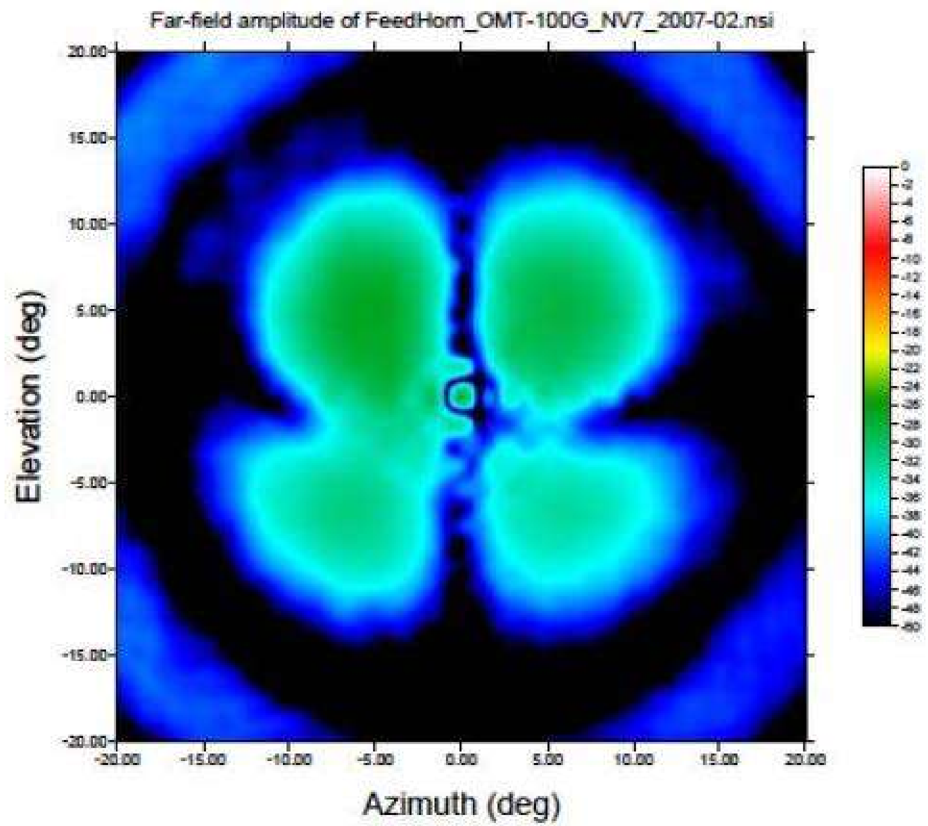
- Instrumental polarization can:
  - cause an unpolarized source to appear polarized
  - alter the apparent polarization of a polarized source
- Two components of instrumental polarization
  - constant or variable across the beam
- Sources of instrumental polarization
  - Antenna structure:
    - Symmetry of the optics
    - Reflections in the optics
    - Curvature of the reflectors
  - Circularity of feed radiation patterns
  - Quality of FE polarization separation (constant across the beam)

# Polarization Beam Patterns

## ALMA Band 3 (100GHz)

Credit: Hunter



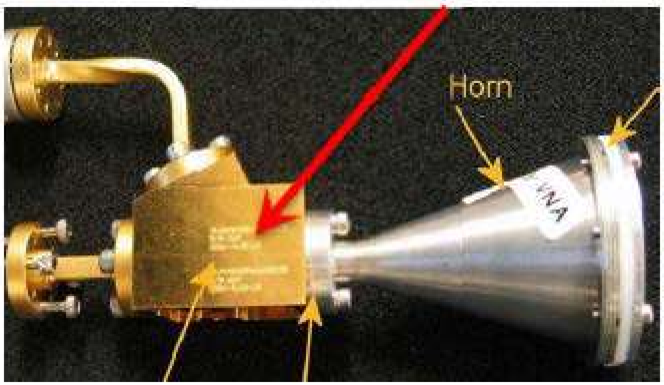




Co-polarization pattern

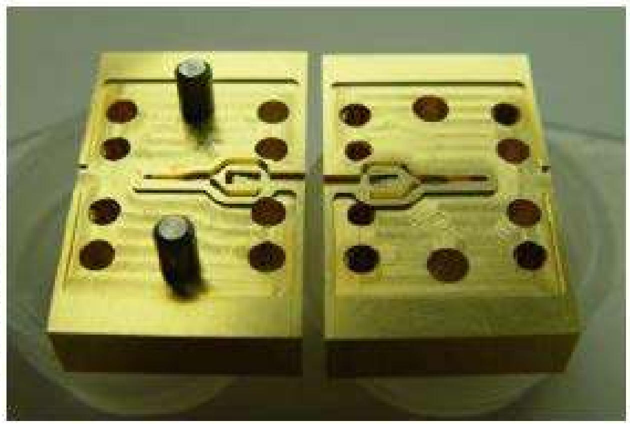
Cross-polarization pattern

# Front End Polarization Separation - I

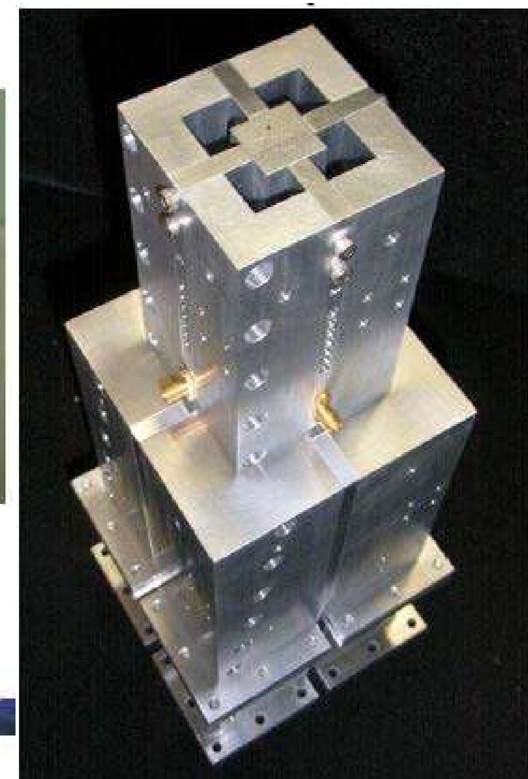
- Dual-polarization receivers needed for best sensitivity and polarization observations
- Two types of devices in use: OMT and wire grid
- Waveguide-type Orthomode Transducer (OMT)
  – After the feed horn; longer wavelength




ALMA Band 3 OMT



ALMA Band 6 OMT

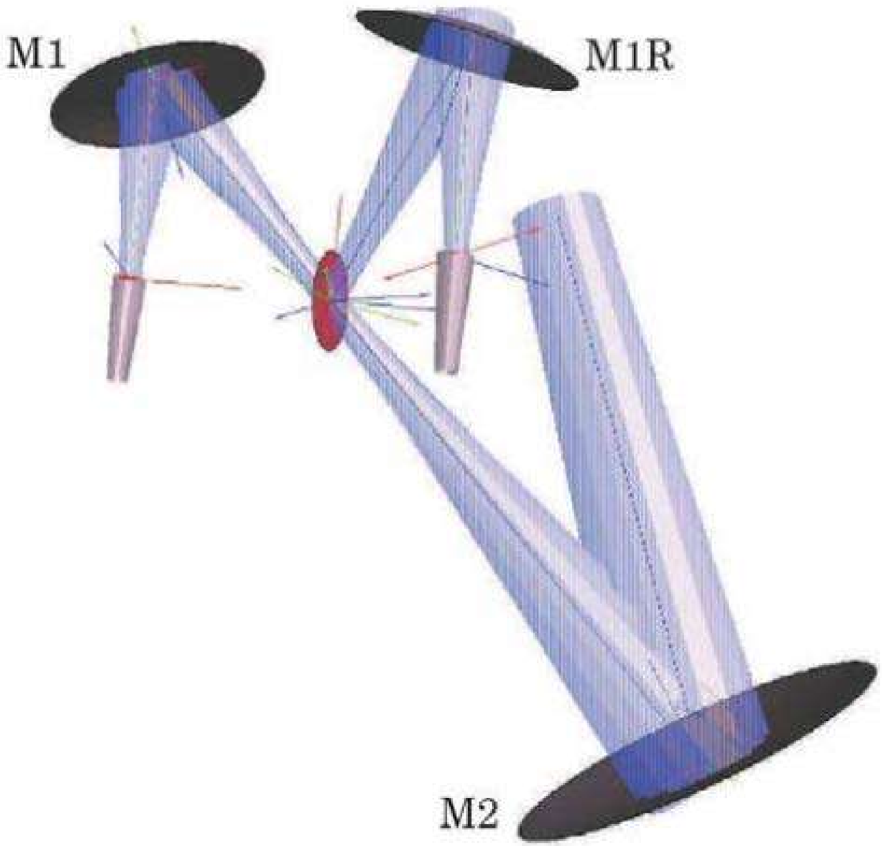


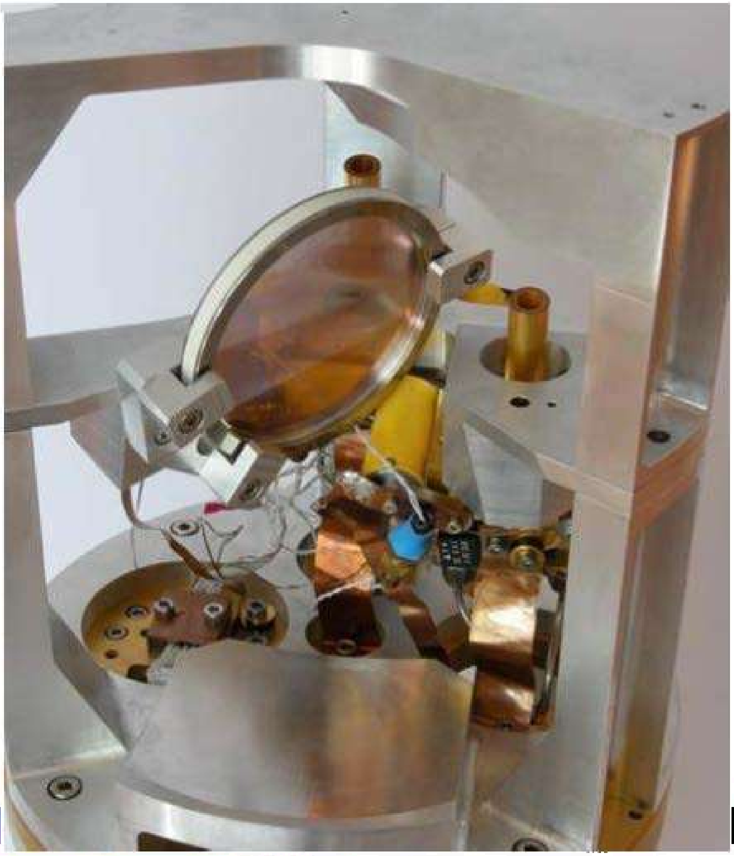
VLA S-band OMT

# Front End Polarization Separation - II

- Quasi-optical: Wire Grid
  - Before the feed horn; shorter wavelength
  - Grid reflects one polarization, passes the other

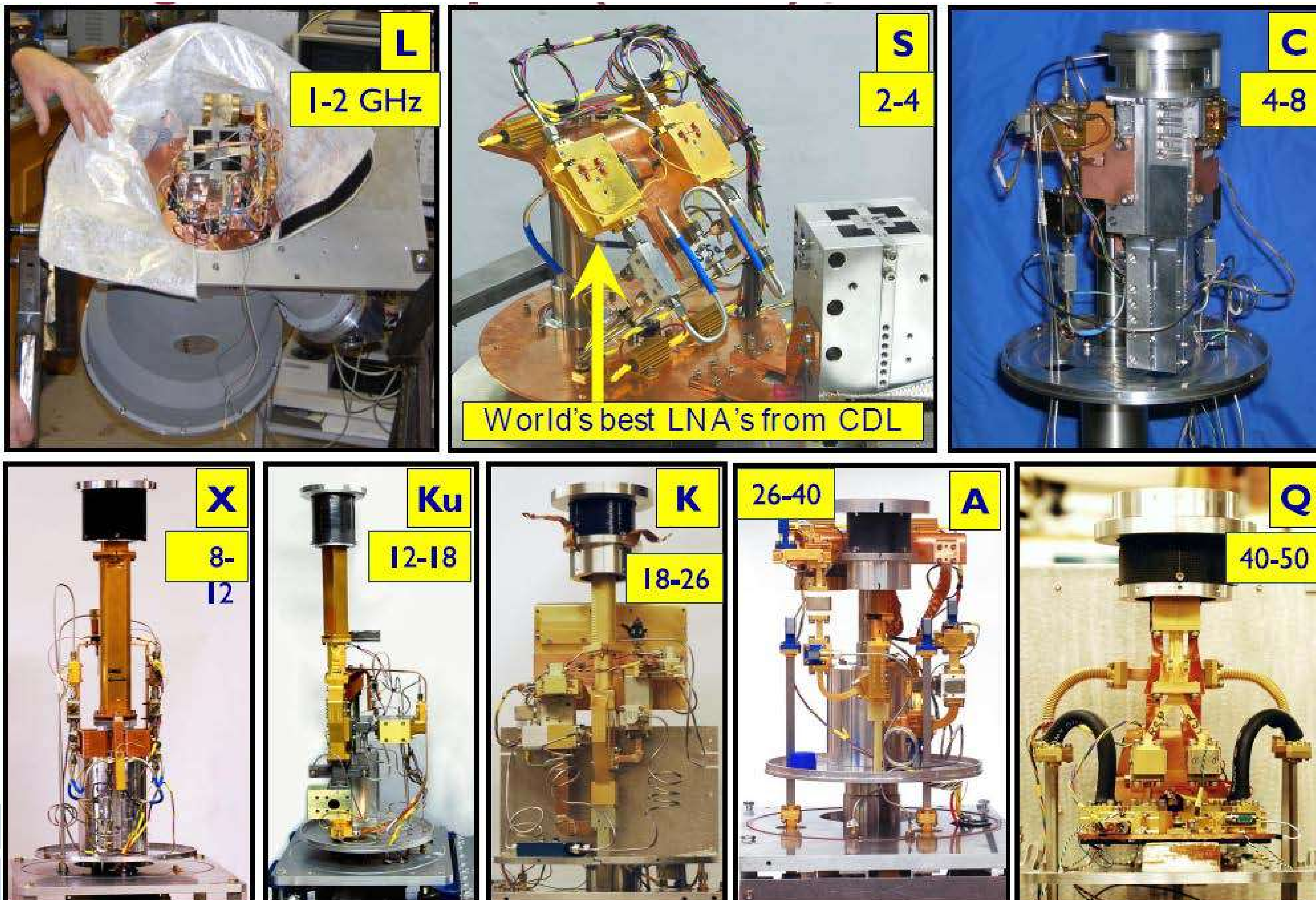
Credit: Hunter



# JVLA Receivers – RF Sections

Credit: Harden & Hayward



# ALMA Receivers

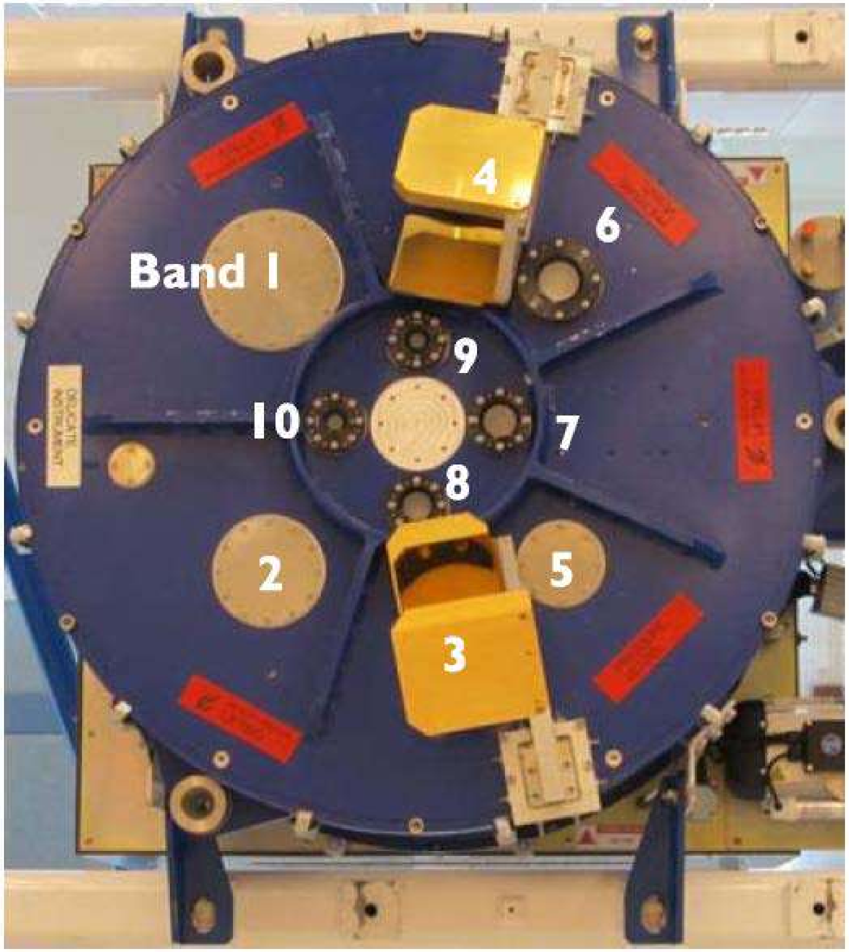
| Lens, OMT | OMT | OMT | Wire grid | OMT | Wire grid |
|---|---|---|---|---|---|

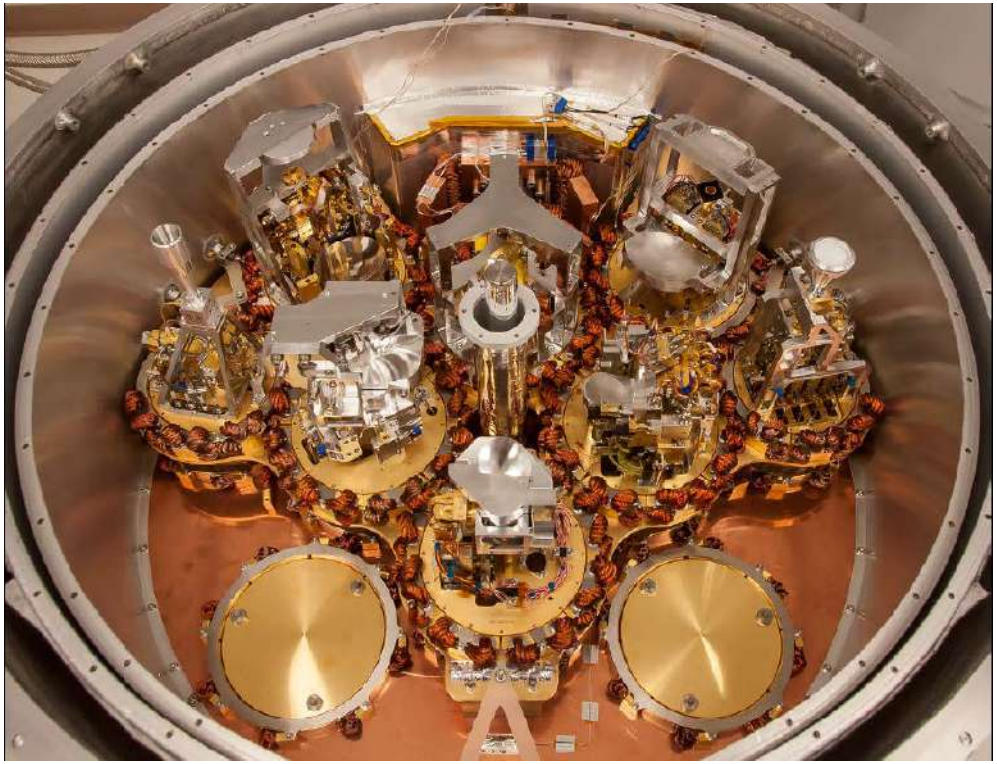

| Band 3 | Band 4 | Band 6 | Band 7 | Band 8 | Band 9 |
|---|---|---|---|---|---|
| 84-116 | 125-163 | 211-275 | 275-373 | 385-500 | 600-720 GHz |

Receivers are dual linear polarization

credit: Hunter

# ALMA Front End Cryostat



# Receivers: Noise Temperature

- Reference the 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

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

$k_B$ = Boltzman's constant ($1.38 \times 10^{-23}$ 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

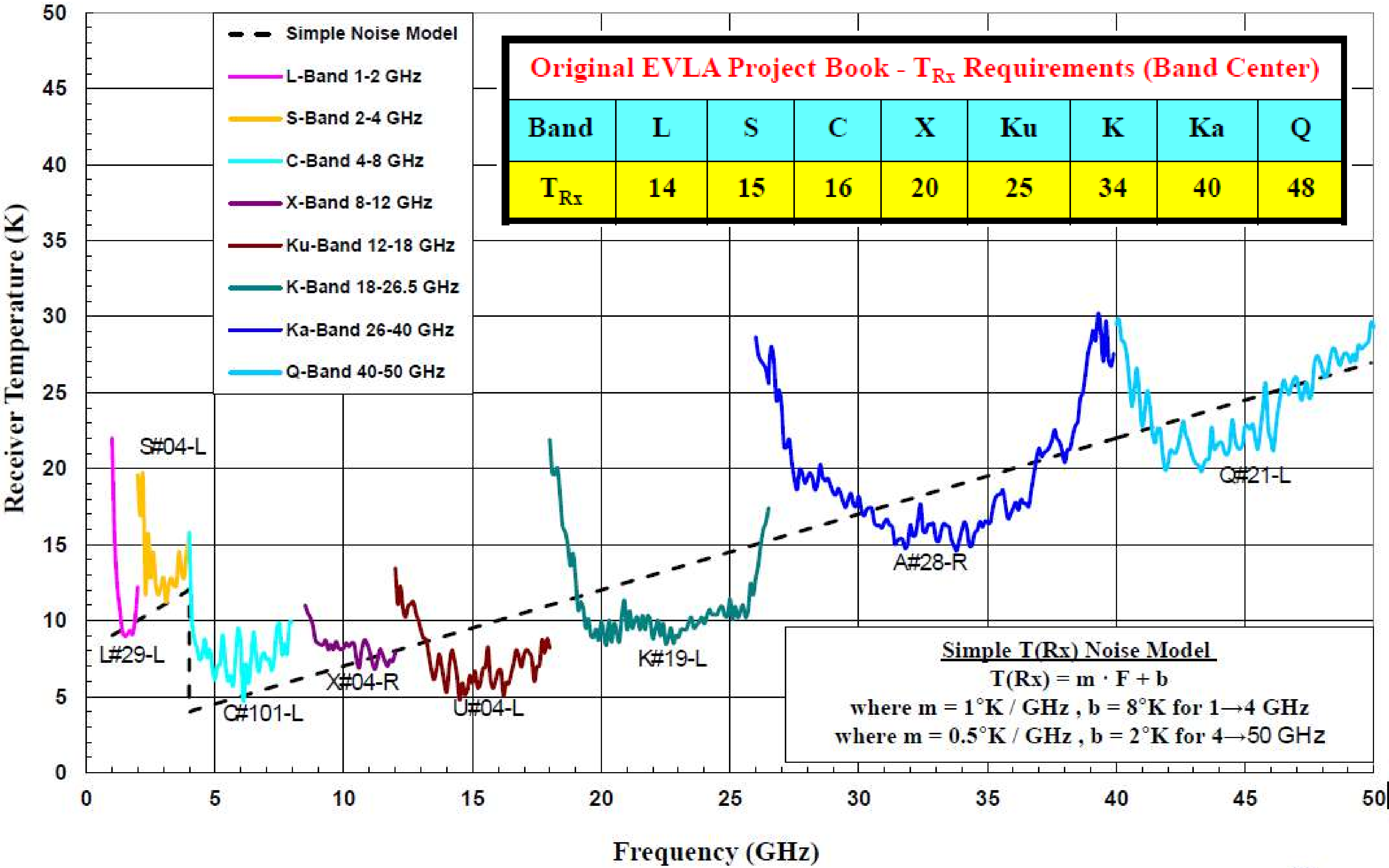
SEFD = Tsys/K (Jy)

EVLA Sensitivities

| Band (GHz) | $\eta$ | $T_{sys}$ | 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 |

# JVLA Receiver Performance

Credit: Hayward




Original EVLA Project Book - $T_{Rx}$ Requirements (Band Center)

| Band | L | S | C | X | Ku | K | Ka | Q |
|---|---|---|---|---|---|---|---|---|
| $T_{Rx}$ | 14 | 15 | 16 | 20 | 25 | 34 | 40 | 48 |

# Additional Information

- General: *Synthesis Imaging in Radio Astronomy II*: ed. Taylor, Carilli, & Perley
- ALMA antennas and receivers: ALMA Technical Handbook at http://almascience.org
- EVLA receivers: http://www.aoc.nrao.edu/~pharden/fe/fe.htm