Antennas & Receivers in Radio Astronomy

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Twentieth Synthesis Imaging Workshop

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NRAO ALMA AUI NSF New Mexico Tech SCIENCE · ENGINEERING · RESEARCH · UNIVERSITY The University of New Mexico New Mexico CONSORTIUM

Purpose & Outline

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

- Based on slides from:
- Rob Selina
- Mark McKinnon
- Craig Walker

Antenna Electronics Block Diagram

EM to Electric Current, w/ Gain

Signal Amplification

G ~ 80 dB (x10^8 in power)

Frequency Down-conversion

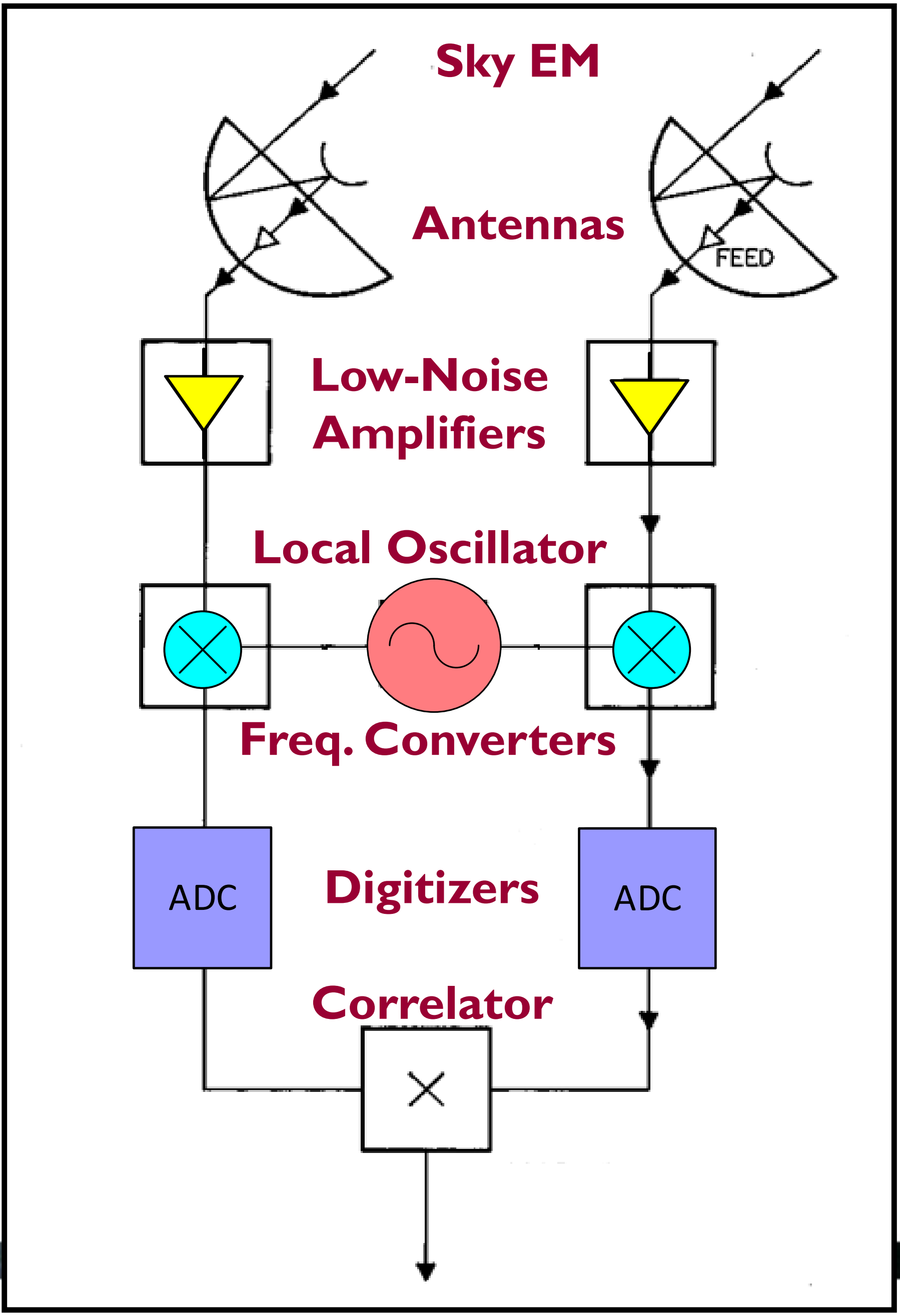
(when needed)

Analog to Digital Converter Input:

Electric Current

~1mW

Limited Frequency

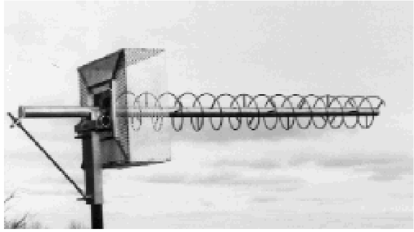


Effects of Antenna Properties on Data

- 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 $(\lambda > 1\text{m})$
  - Dipole, Yagi, Helix, or small arrays of each type
- Reflector antennas $(\lambda < 1\text{m})$
- Hybrid antennas $(\lambda \approx 1\text{m})$
  - 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, $A_0 = \eta A$

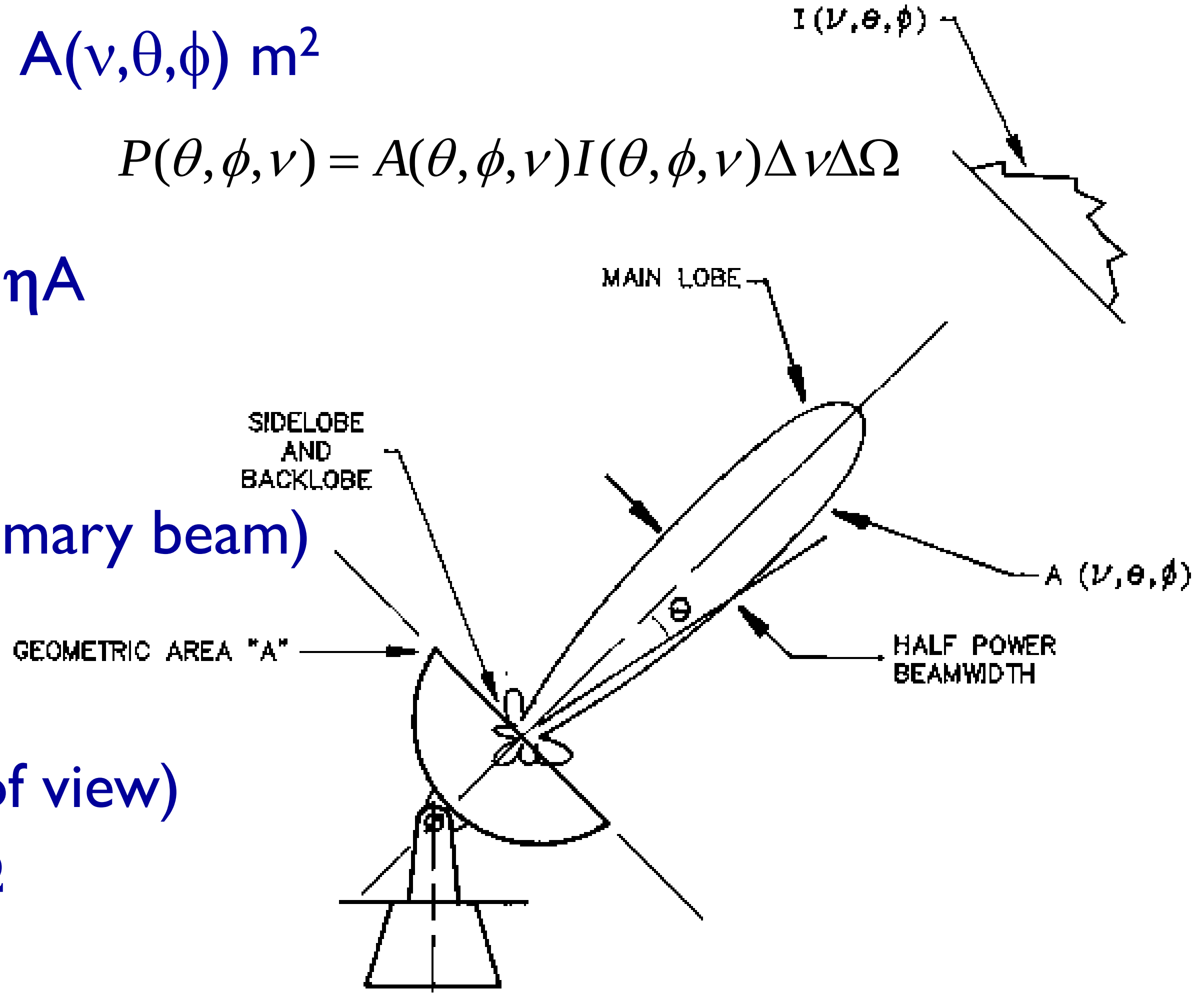
η = aperture efficiency

Normalized pattern (primary beam)

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

Beam solid angle (field of view)

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

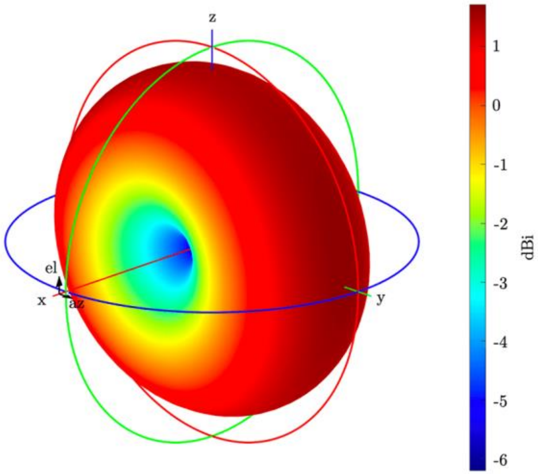


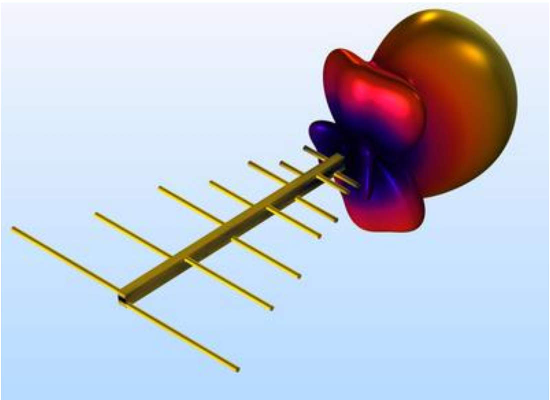
Terminology & Definitions - II

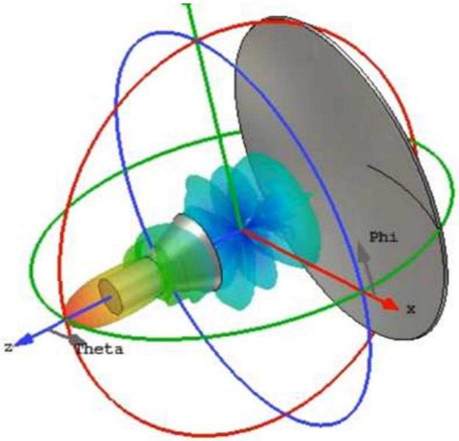
- $A_0 \Omega_A = \lambda^2$ Effective area (gain) & solid angle (field of view)
  - Can have large effective area or large solid angle, but not both at the same time
- Antenna sidelobes and backlobes
  - Increase system temperature due to ground pick up
  - Make antenna susceptible to RFI
  - Sidelobes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

Beam Patterns

- Half wave dipole
- Yagi
- Parabolic



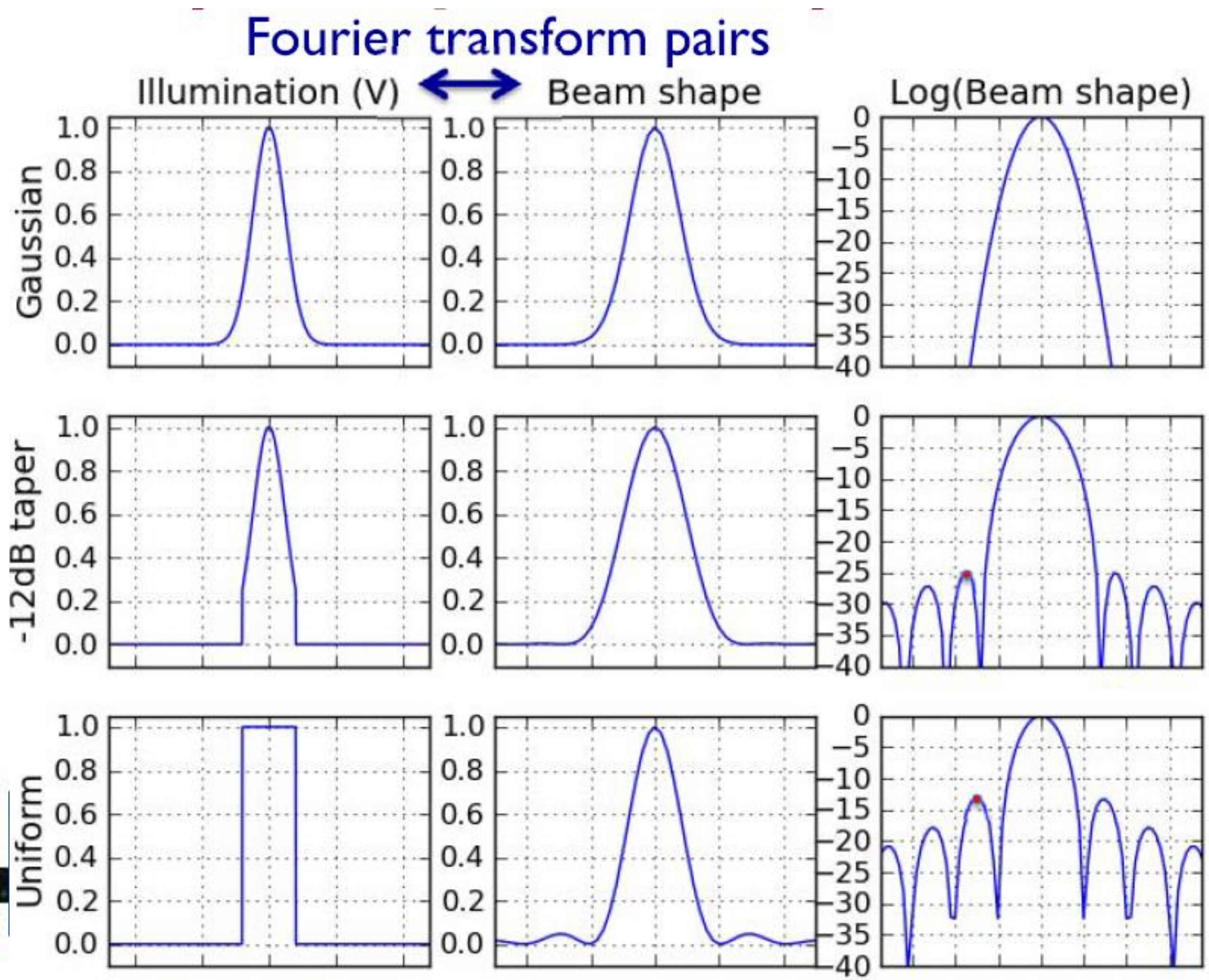




- Credit Timmons 2022
- Credit COMSOL
- Credit Phaebua 2021

Illumination-Beam Shape Comparisons

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

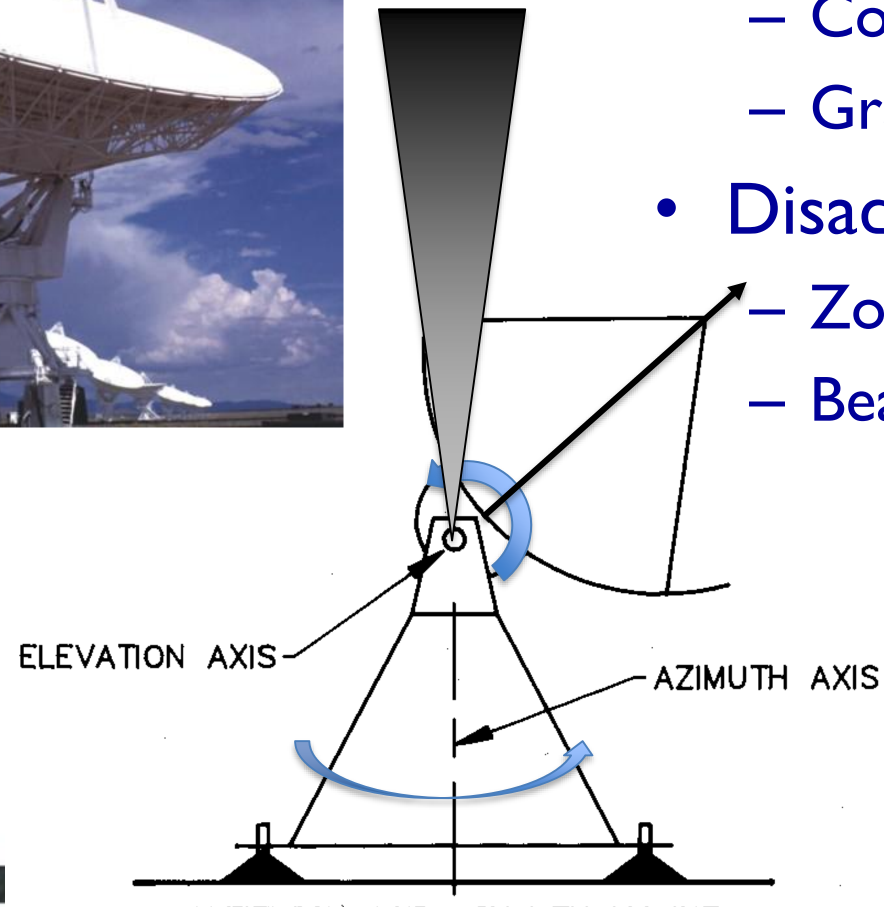


Credit: Hunter

θ_{3dB} = 1.02/D
First null = 1.22/D
D = diameter in wavelengths

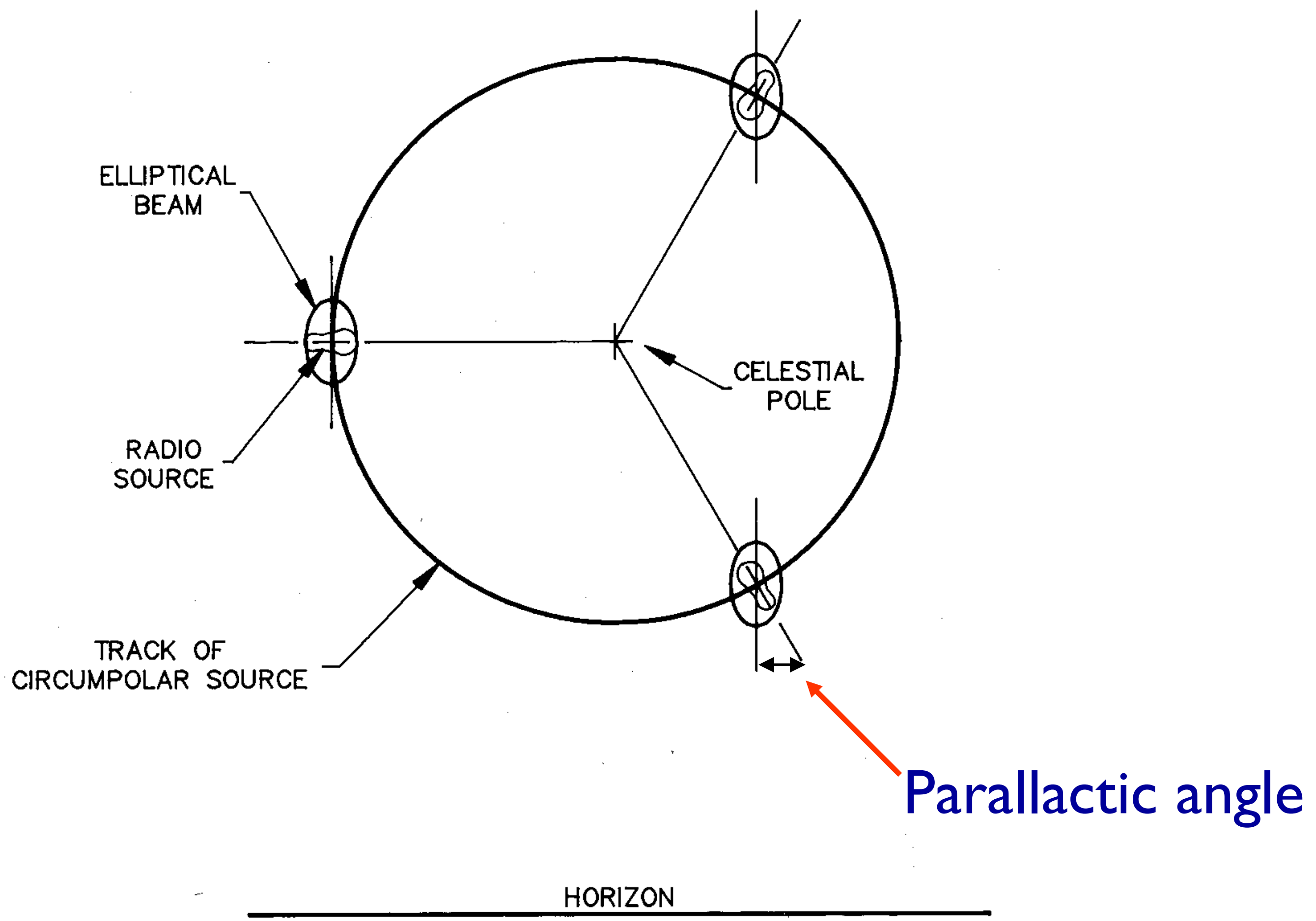
Antenna Mounts: Altitude over Azimuth

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



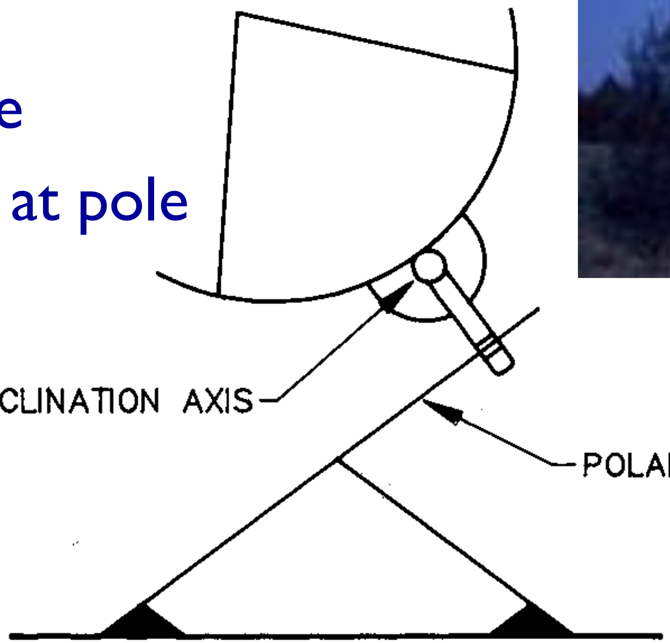
ALTITUDE OVER AZIMUTH MOUNT

Alt-Az: Beam Rotation on the Sky



Antenna Mounts: Equatorial

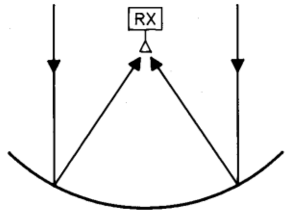
- Advantages
  - Tracking accuracy
  - Beam doesn't rotate
- Disadvantages
  - Cost
  - Gravity performance
  - Sources on horizon at pole



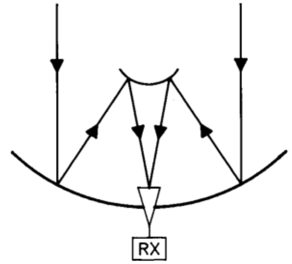
Antenna Optical Configurations

GMRT

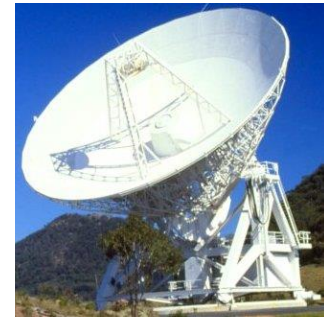
Prime Focus



Cassegrain

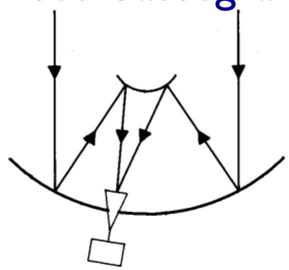


ATCA

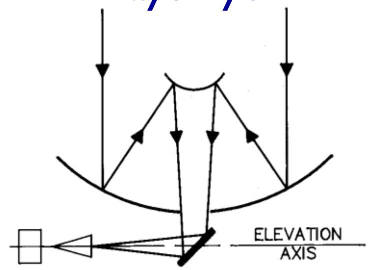


VLA
VLBA
ALMA

Offset Cassegrain



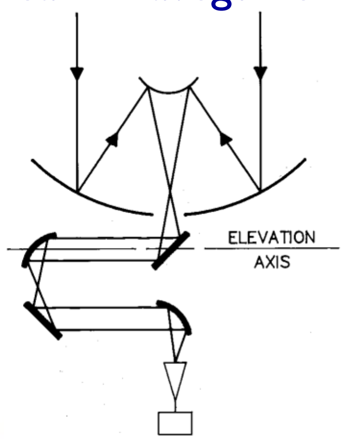
Naysmyth



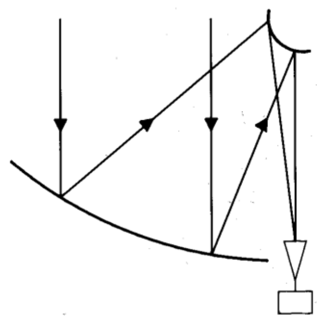
CARMA

NRO

Beam Waveguide



Dual Offset



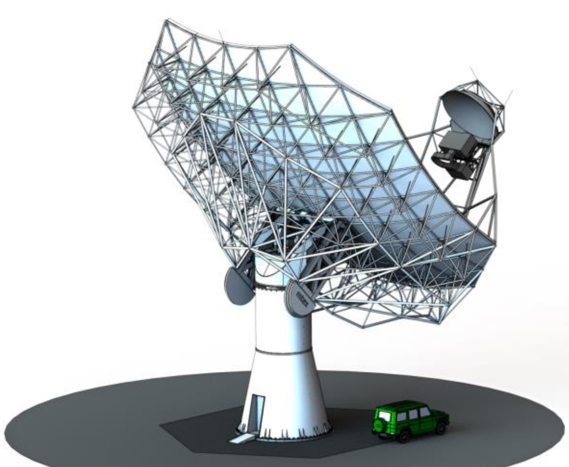
GBT
SKA
ngVLA

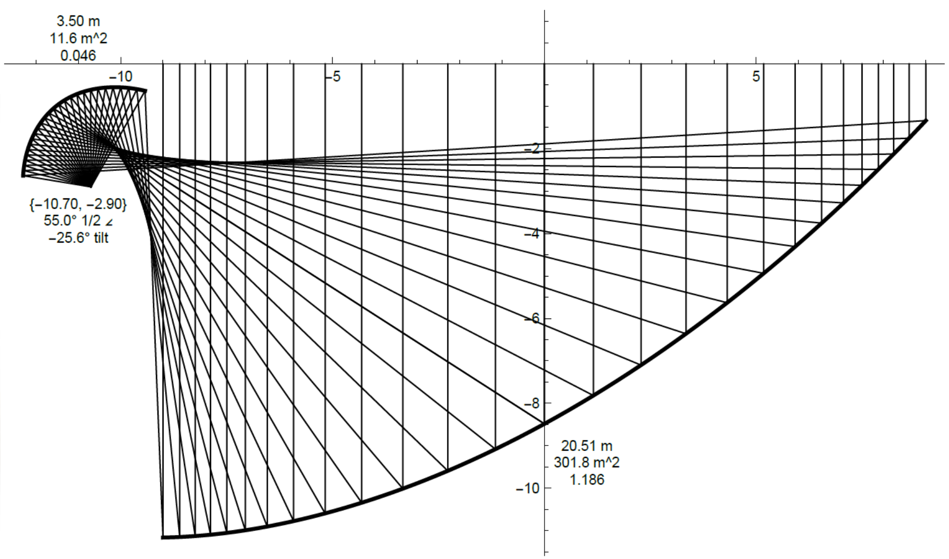
Optical Configurations, Pros & Cons - I

- 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 Cassegrain 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

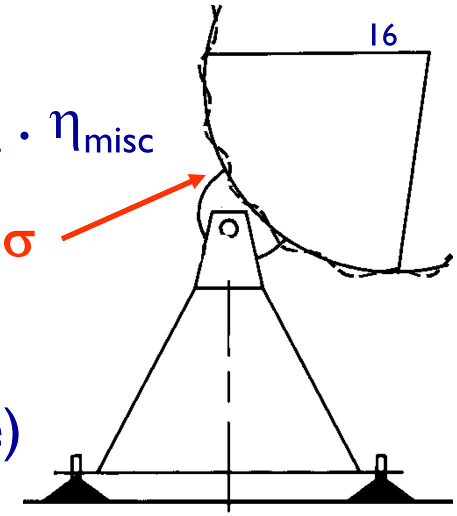
Optical Configurations, Pros & Cons - II

- Offset optics (Gregorian or Cassegrain)
  - Unblocked aperture:
    - higher aperture efficiency, lower sidelobes, less scatter / lower system temperature
  - Practical low-frequency feed designs.
  - Support structure of offset geometry is more complex and expensive
  - No rotational symmetry – more expensive panel tooling due to multiple panel sizes





Aperture Efficiency



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

η_{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)

η_{bl} = Blockage efficiency. Caused by subreflector and its support structure

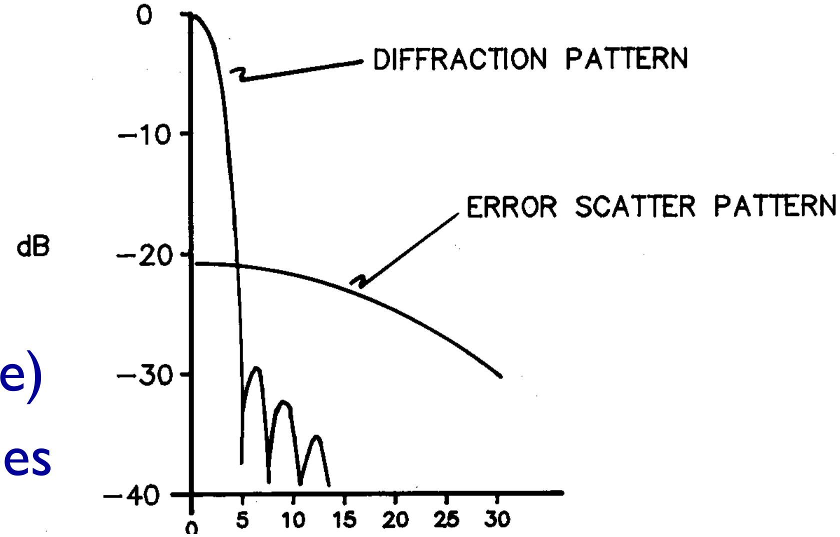
η_s = Feed spillover efficiency. Fraction of power radiated by feed intercepted by subreflector

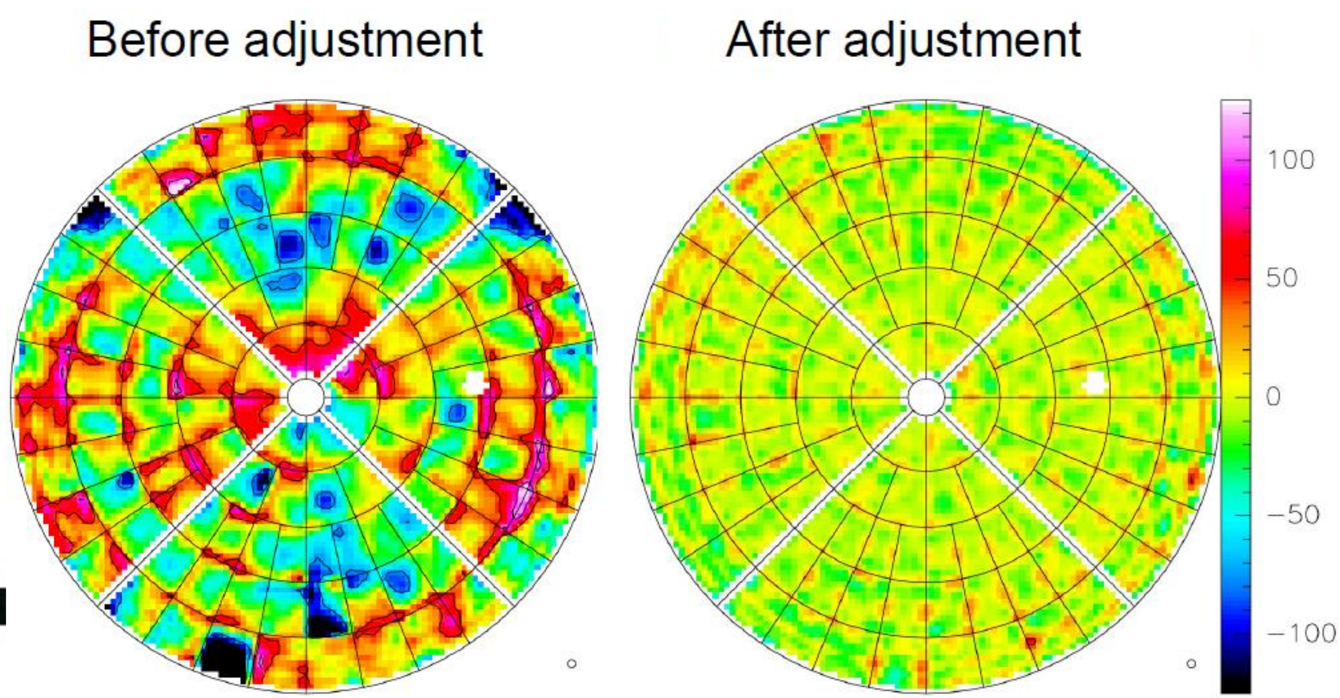
η_t = Illumination taper efficiency. Outer parts of reflector illuminated at lower level than inner part

η_{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



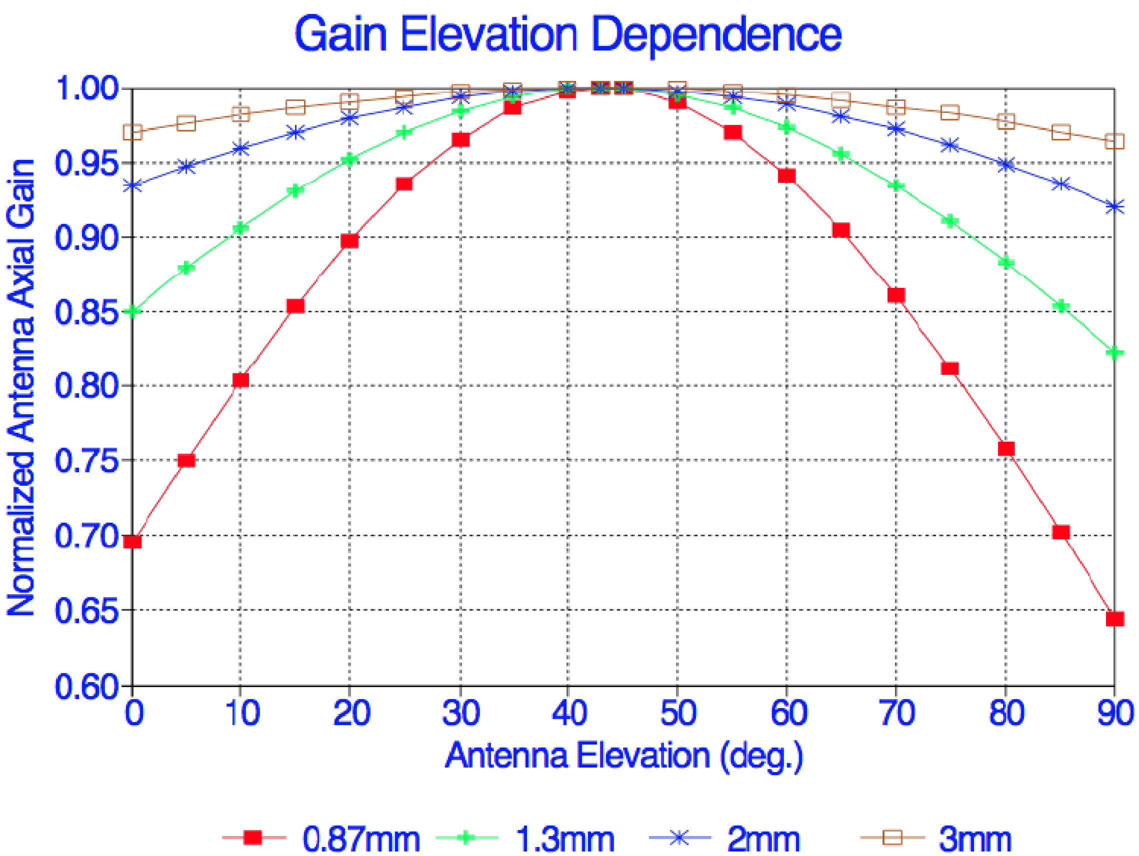


ALMA surface panel adjustment: phase map

Antenna Gain - I

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

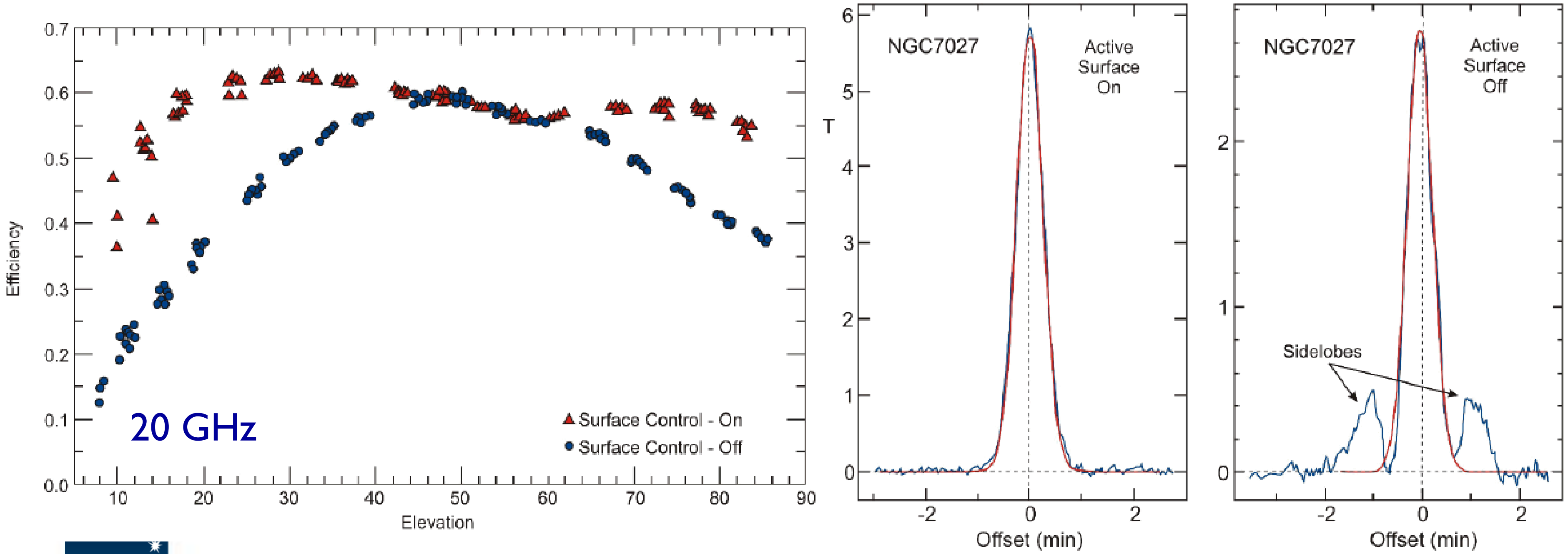
IRAM 30m (predicted, 1999)



credit: Hunter

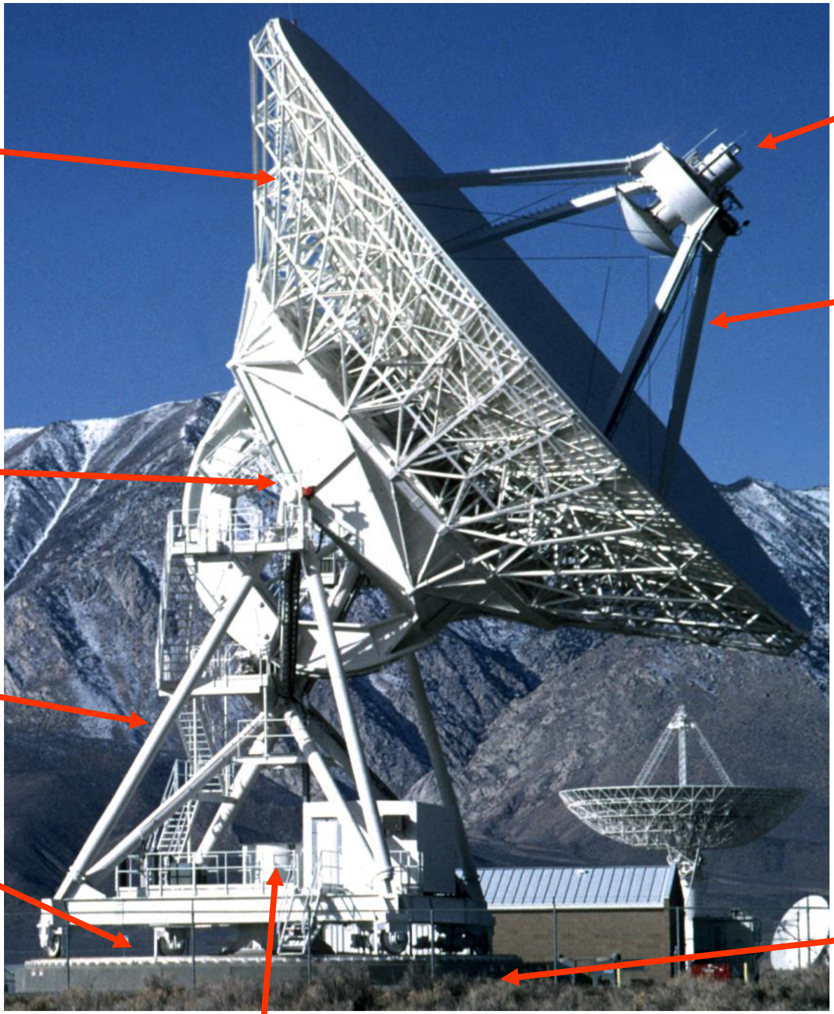
Antenna Gain - II

- 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

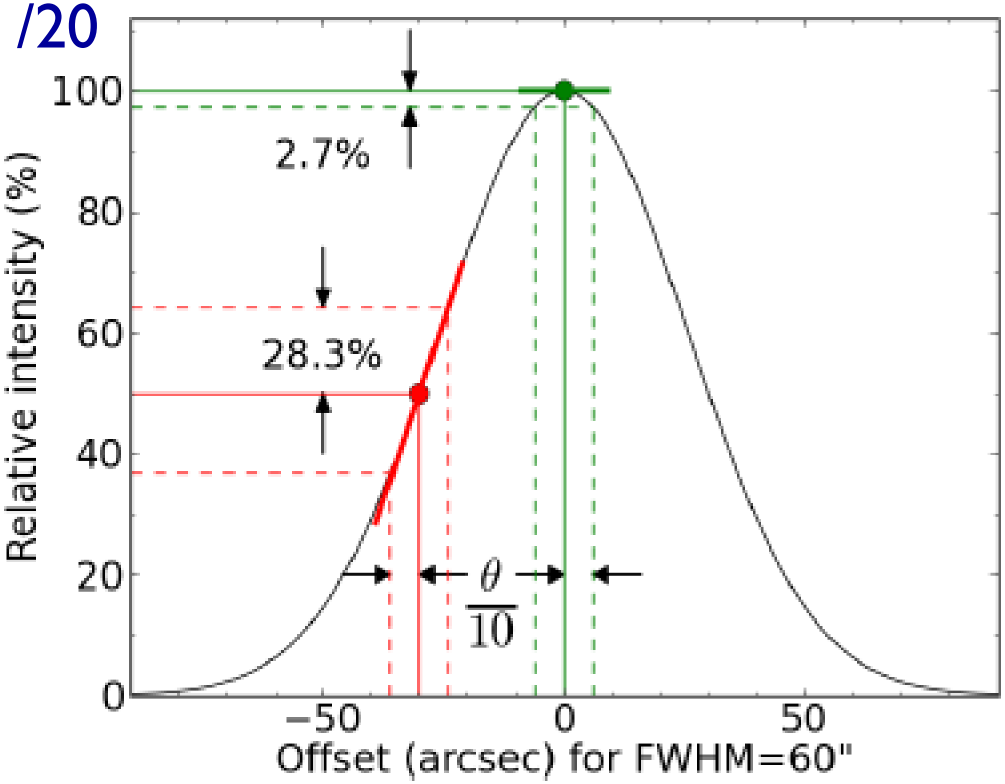
Antenna Pointing: Practical Considerations



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

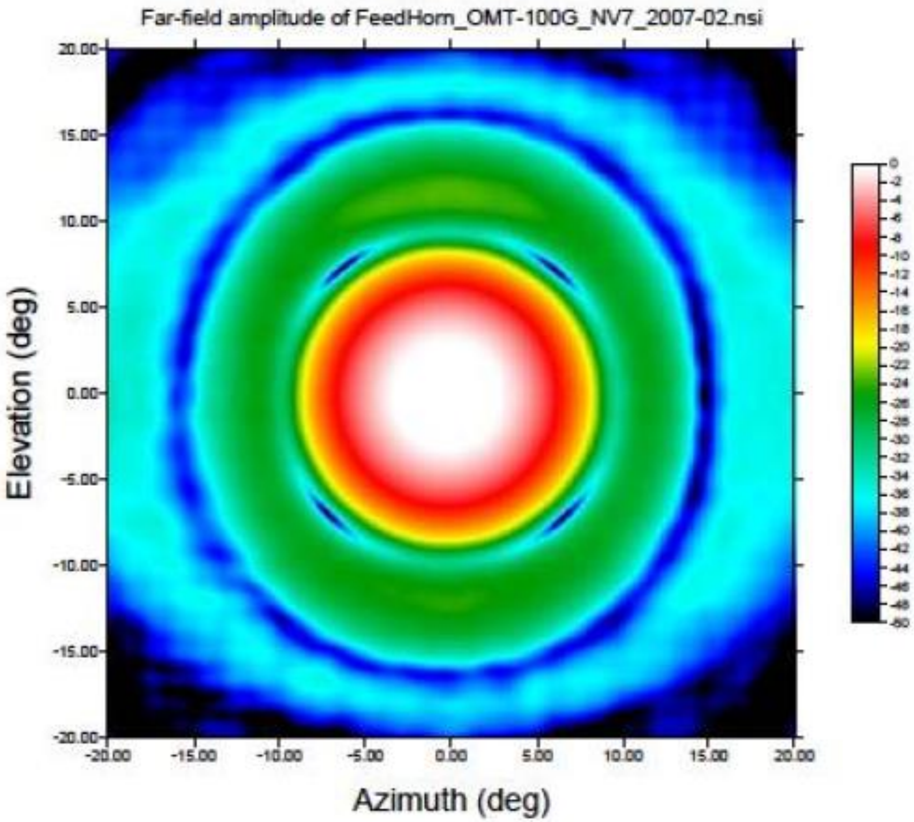
Antenna Polarization Properties

- 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)

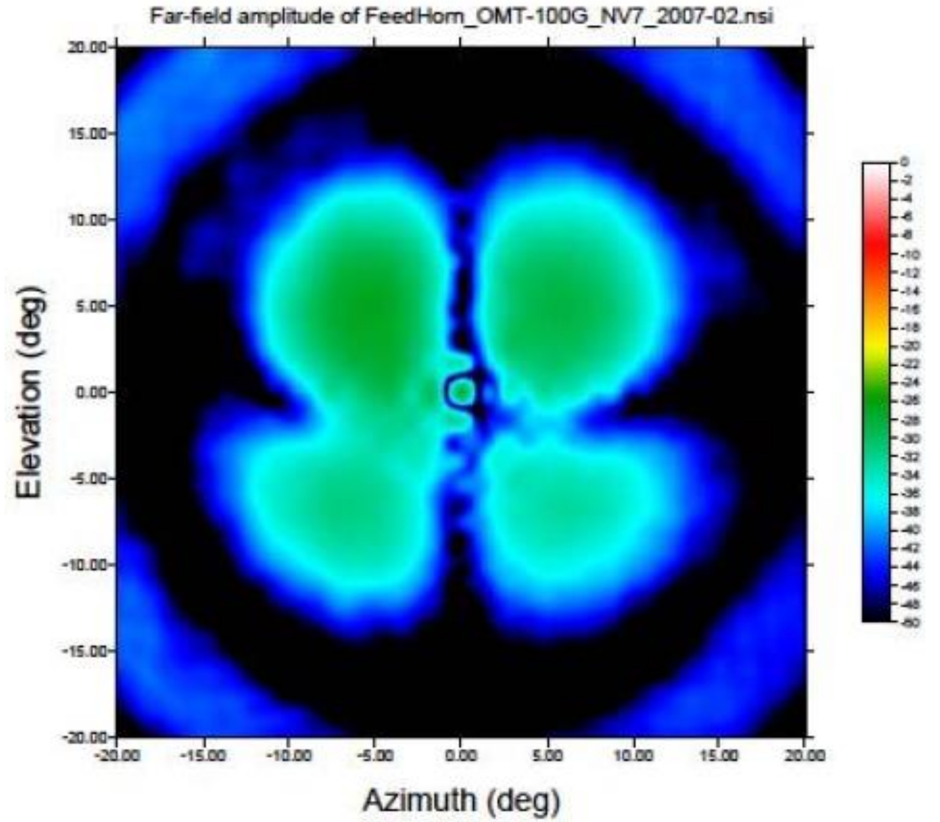
Polarization Beam Patterns

ALMA Band 3 (100GHz)

Credit: Hunter



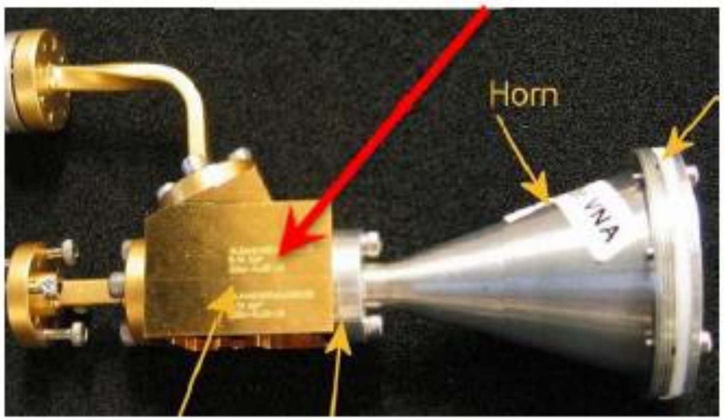
Co-polarization pattern



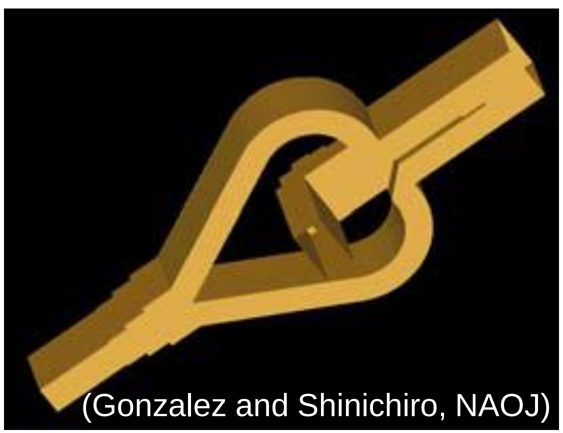
Cross-polarization pattern

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

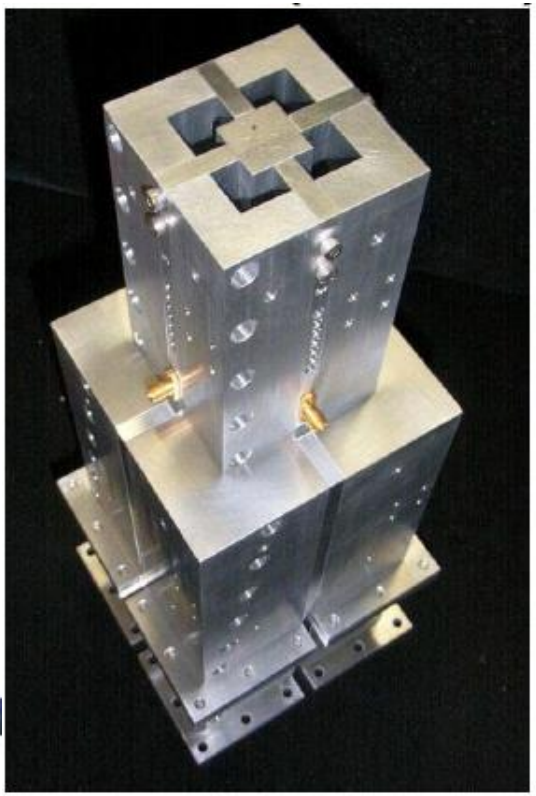


ALMA Band 3 OMT



(Gonzalez and Shinichiro, NAOJ)

ALMA Band 2+3 OMT (inside)

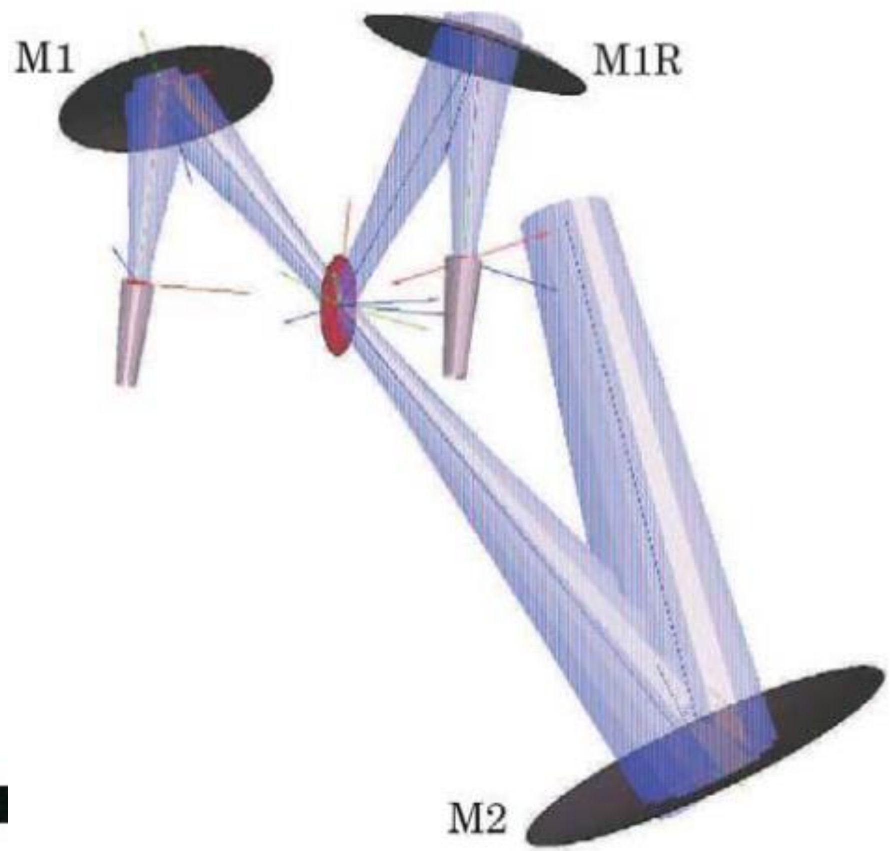


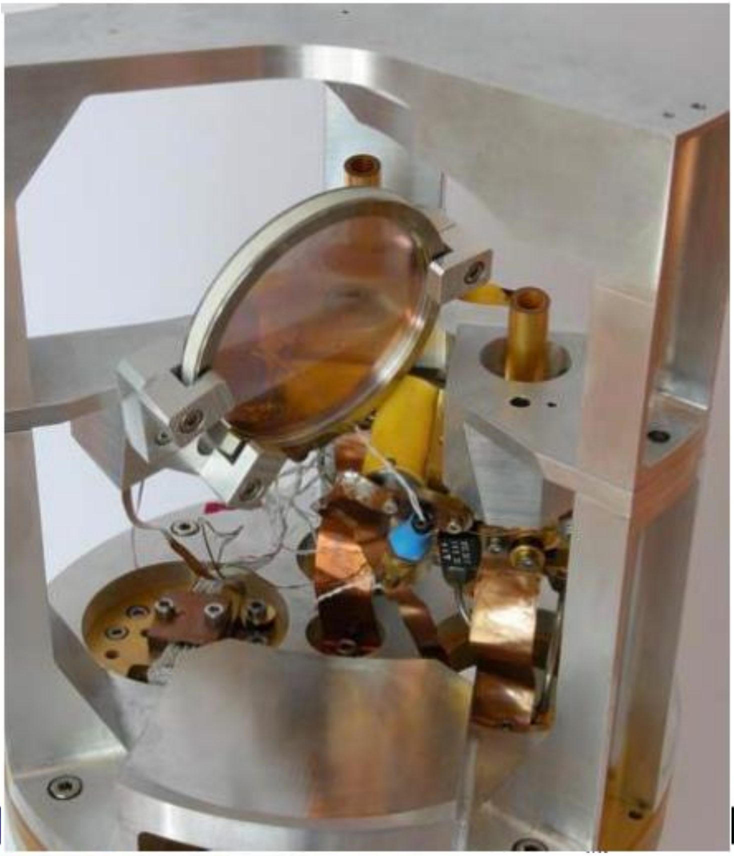
VLA S-band OMT

Front End Polarization Separation - II

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

Credit: Hunter





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

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

Receivers: SEFD

$$T_{sys} = T_{receiver} + T_{ground} + T_{sky}$$

$$T_{sky} = T_{atm} \times (1 - e^{-t\ \sin(elv)}) + T_{CMB} + T_{RB}$$

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

S = source flux (Jy)

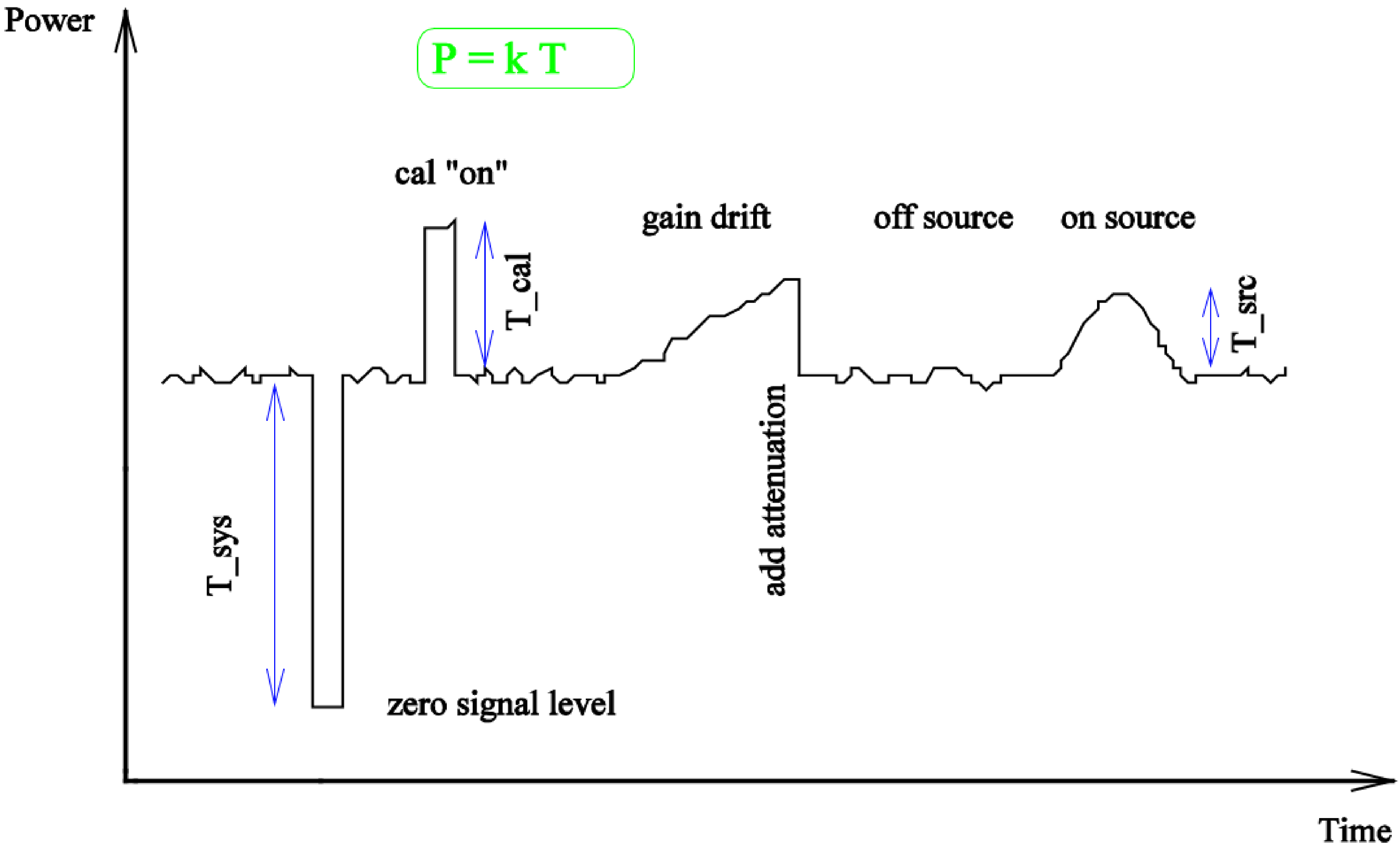
SEFD = system equivalent flux density

SEFD = Tsys/K (Jy)

EVLA Antenna 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

Receivers: Noise Temperature



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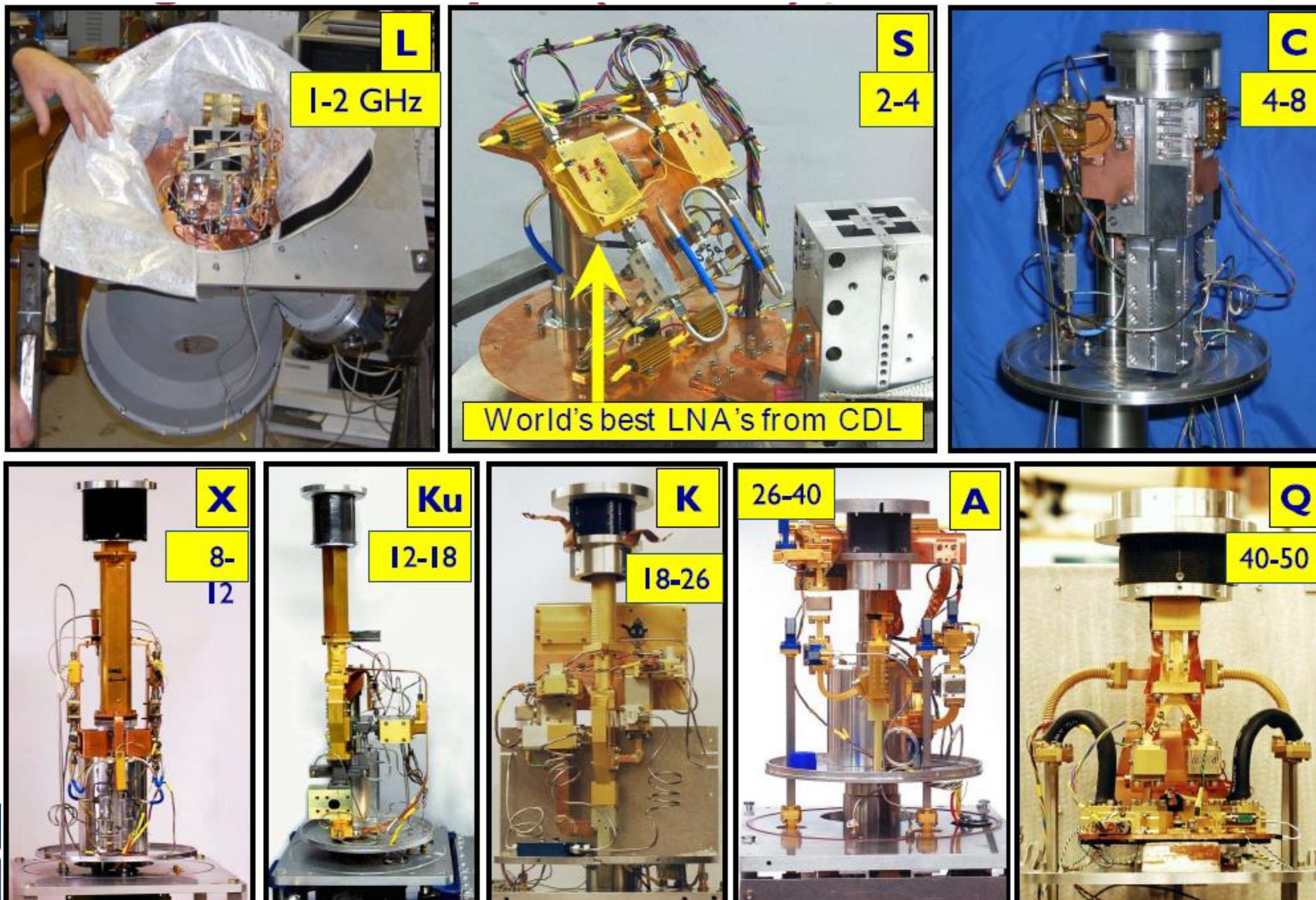
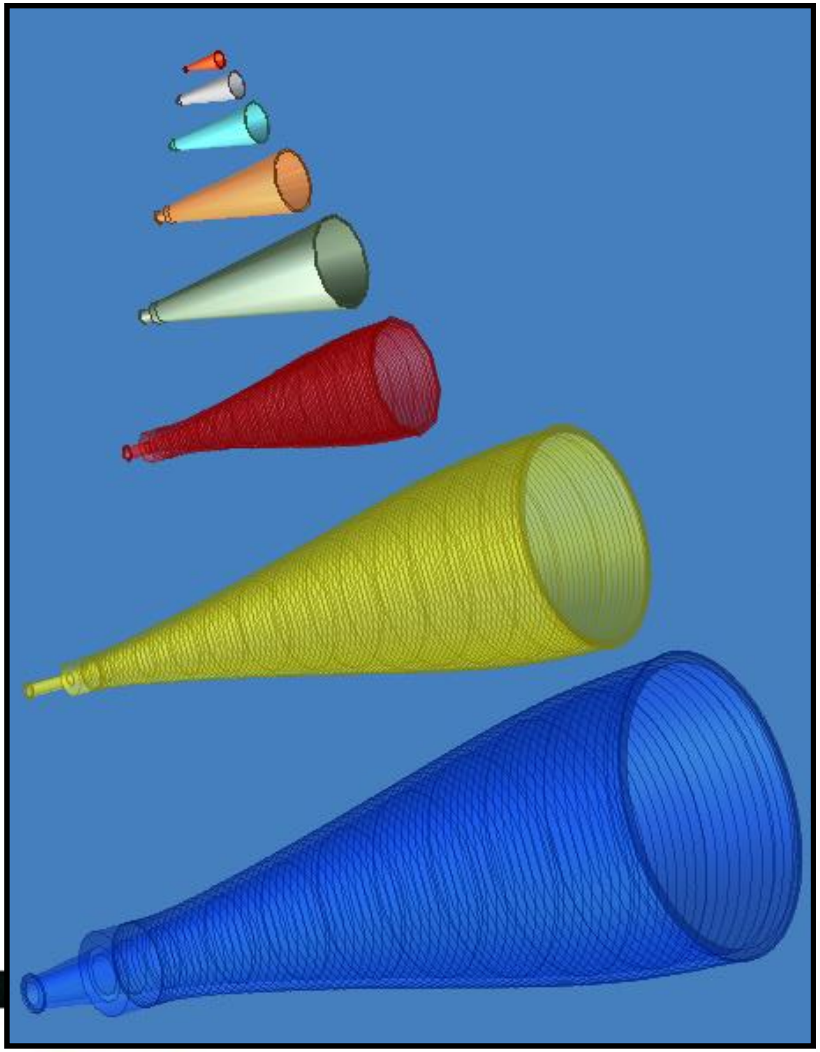
JVLA Receivers – RF Sections

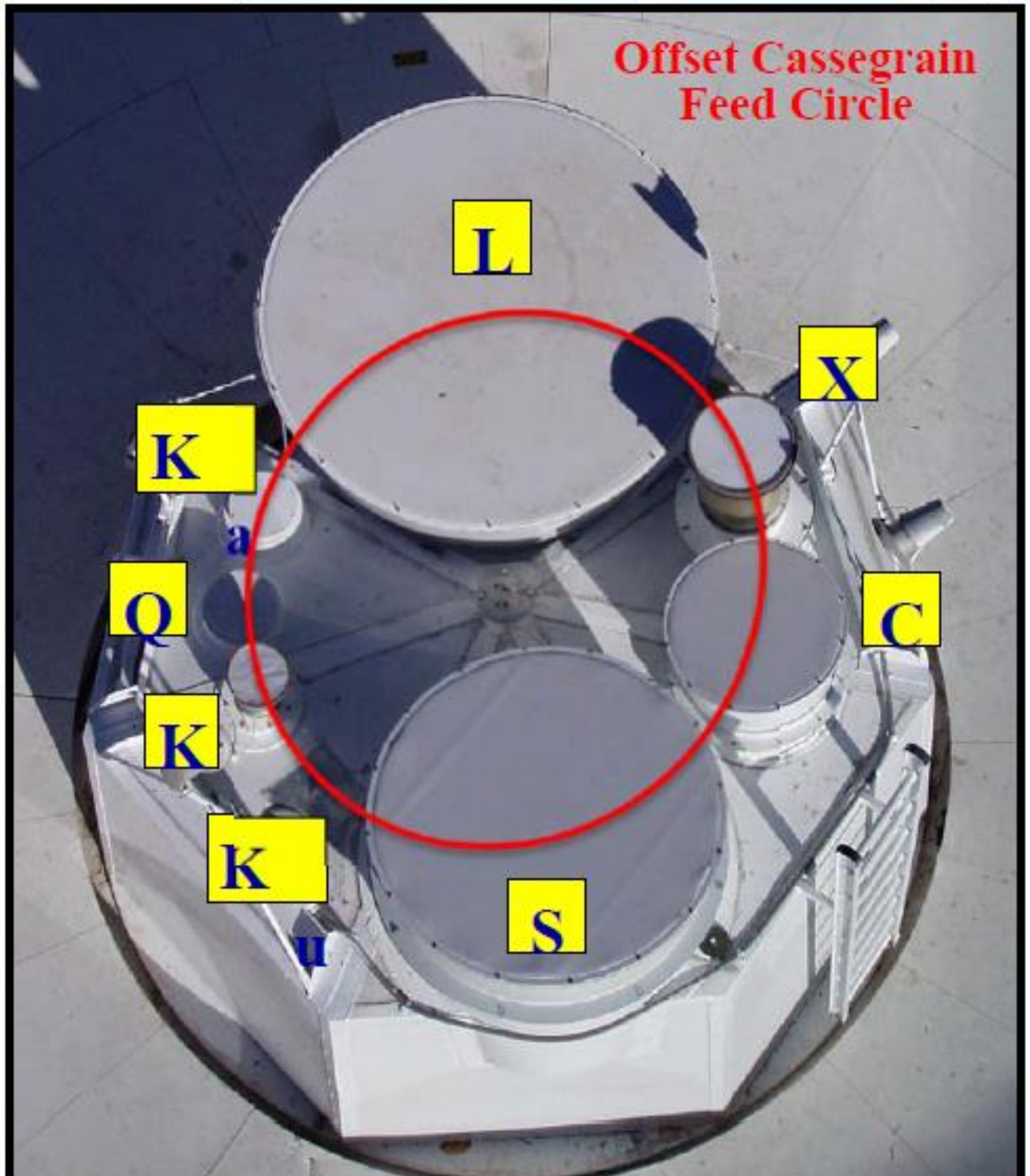
Credit: Harden & Hayward



JVLA Feed Horns

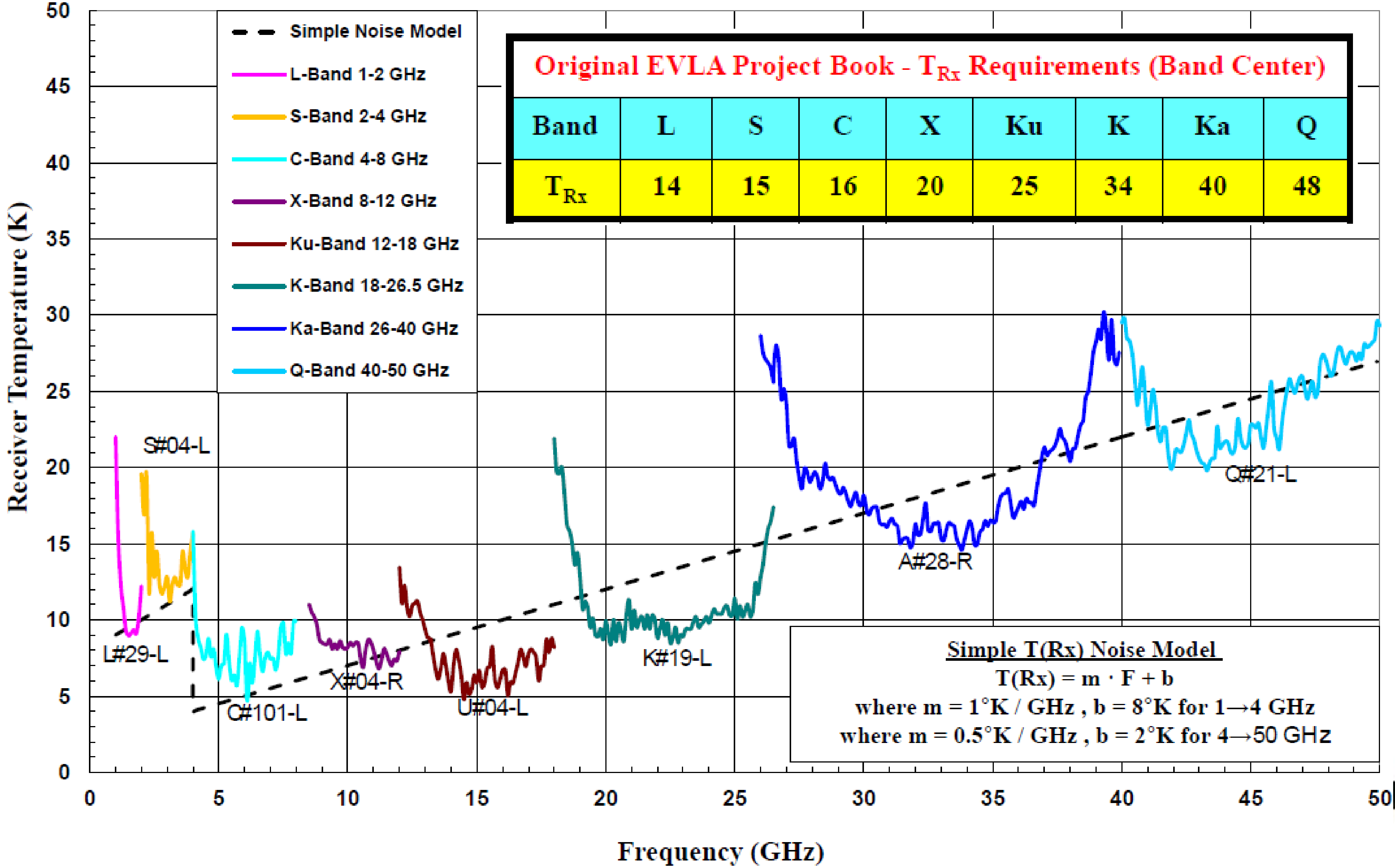
Credit: Ruff & Hayward





JVLA Receiver Performance

Credit: Hayward

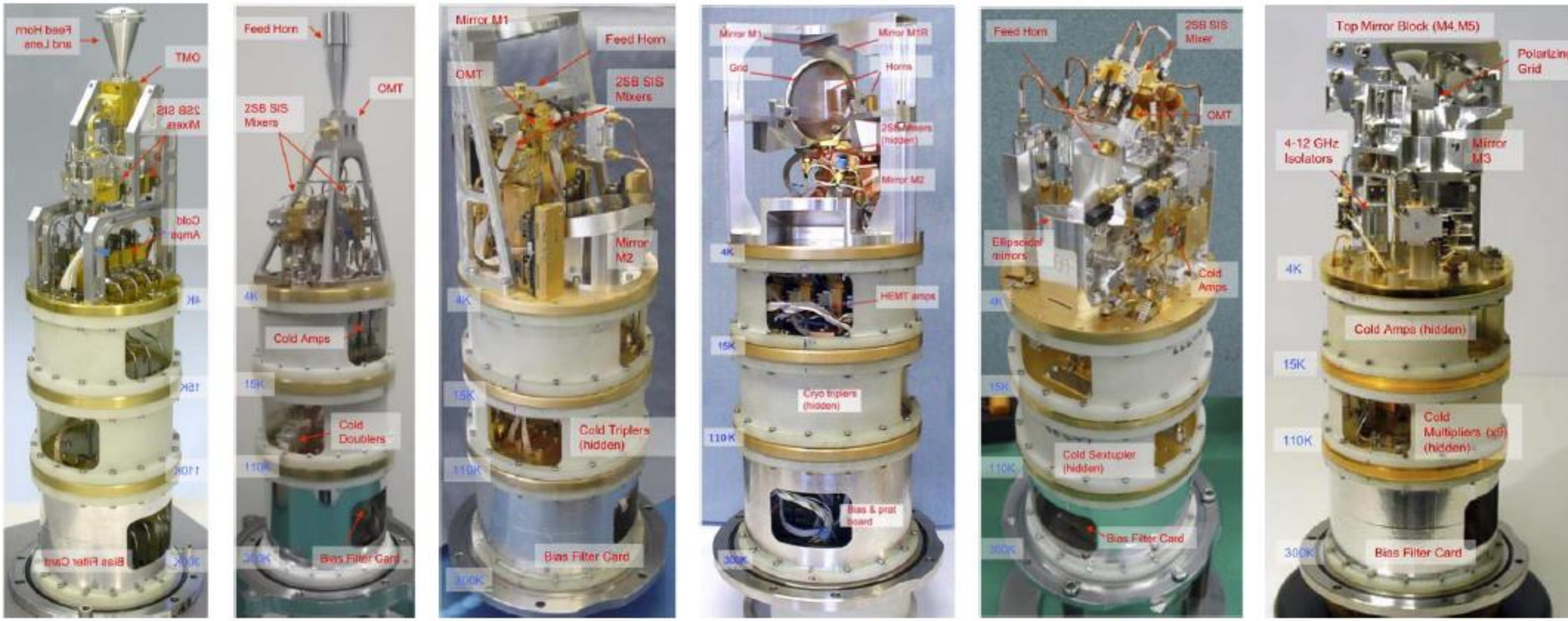


Original EVLA Project Book - T_{Rx} Requirements (Band Center)

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

ALMA Receivers

Lens, OMT	OMT	OMT	Wire grid	OMT	Wire grid

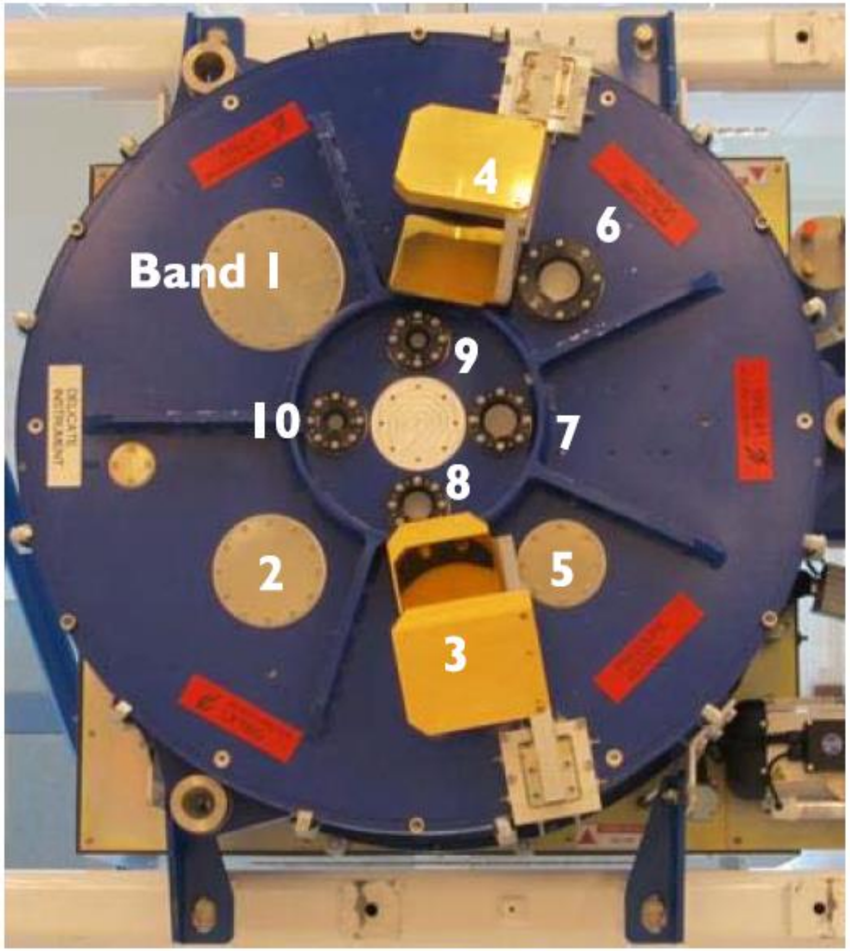


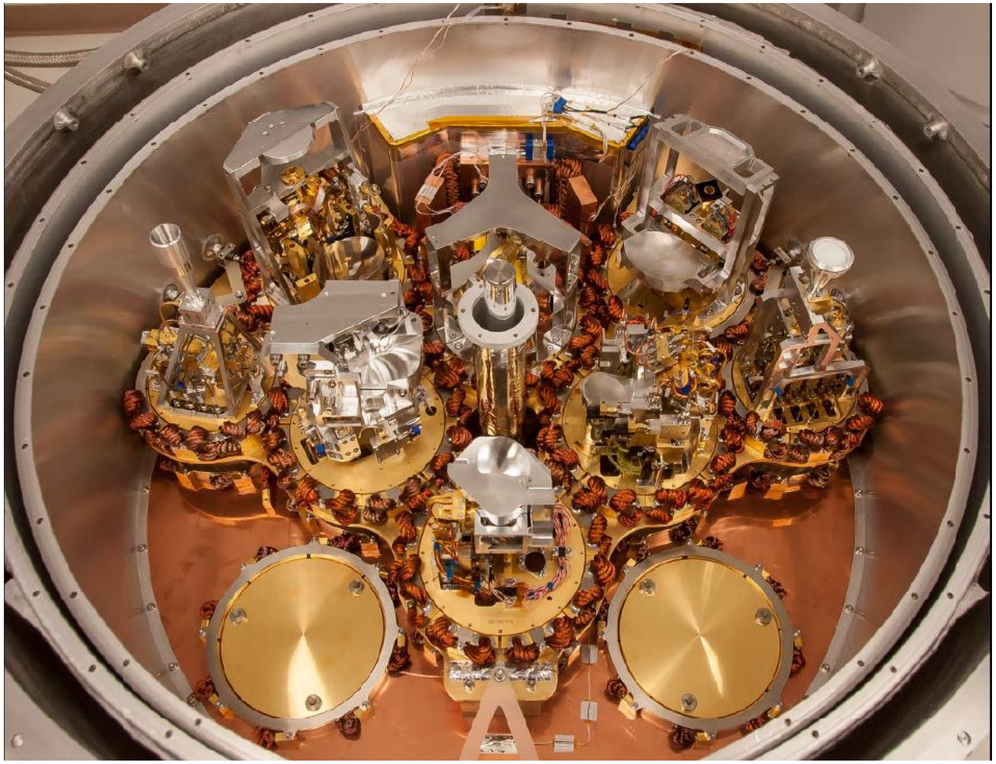
Band 3	Band 4	Band 6	Band 7	Band 8	Band 9
84-116	125-163	211-275	275-373	385-500	600-720 GHz

Receivers are dual linear polarization

credit: Hunter

ALMA Front End Cryostat





Closing Thoughts

- Antenna amplitude/phase pattern causes amplitude/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.
- Deformations of the antenna surface can cause amplitude and phase errors, especially at short wavelengths.
- Even state-of-the-art receivers add thermal noise that is often larger than the source signal.
- Receiver gain and noise can fluctuate with time and physical temperature.

However, knowledge of the system and it's behaviors enables you to compensate/correct many of these effects through Calibration.

Additional Information

- General: *Synthesis Imaging in Radio Astronomy II*: ed. Taylor, Carilli, & Perley
  - https://leo.phys.unm.edu/~gbtaylor/astr423/s98book.pdf
- ALMA antennas and receivers: ALMA Technical Handbook
  - https://almascience.nrao.edu/proposing/technical-handbook
- EVLA receivers:
  - http://www.aoc.nrao.edu/evla/admin/projbook/chap5.pdf
- ngVLA Antennas & Receivers:
  - https://ngvla.nrao.edu/page/projdoc