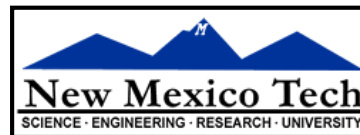# Antennas & Receivers in Radio Astronomy

Mark McKinnon

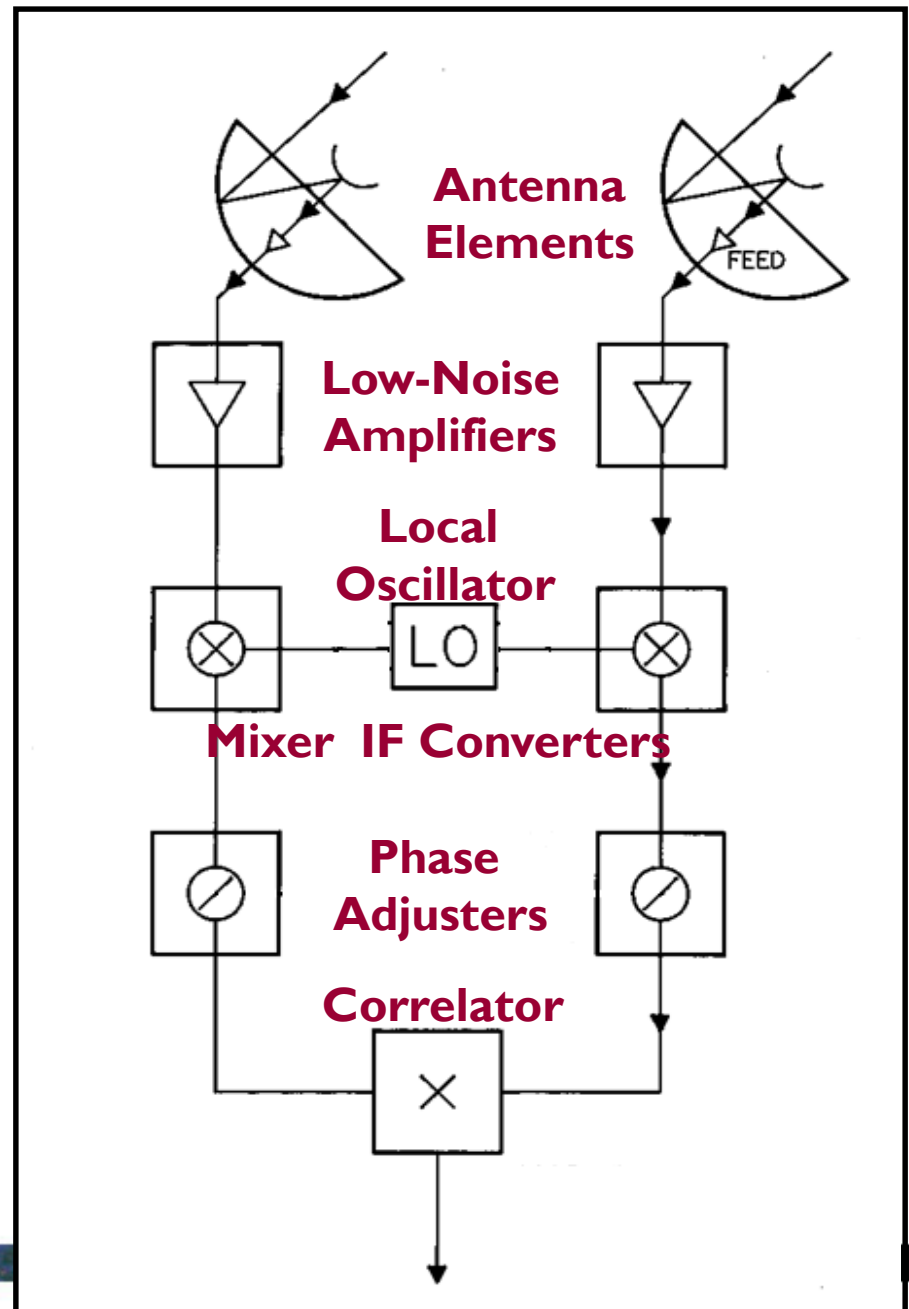Sixteenth Synthesis Imaging Workshop

16-23 May 2018

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

Antenna Elements

Low-Noise Amplifiers

Local Oscillator

Mixer IF Converters

Phase Adjusters

Correlator

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

16th Synthesis Imaging Workshop
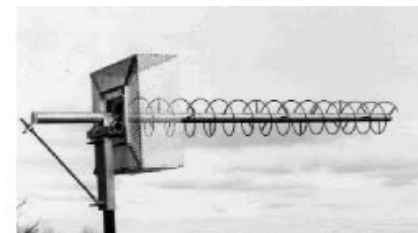
Terminology & Definitions - I

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, $A_0 = \eta A$

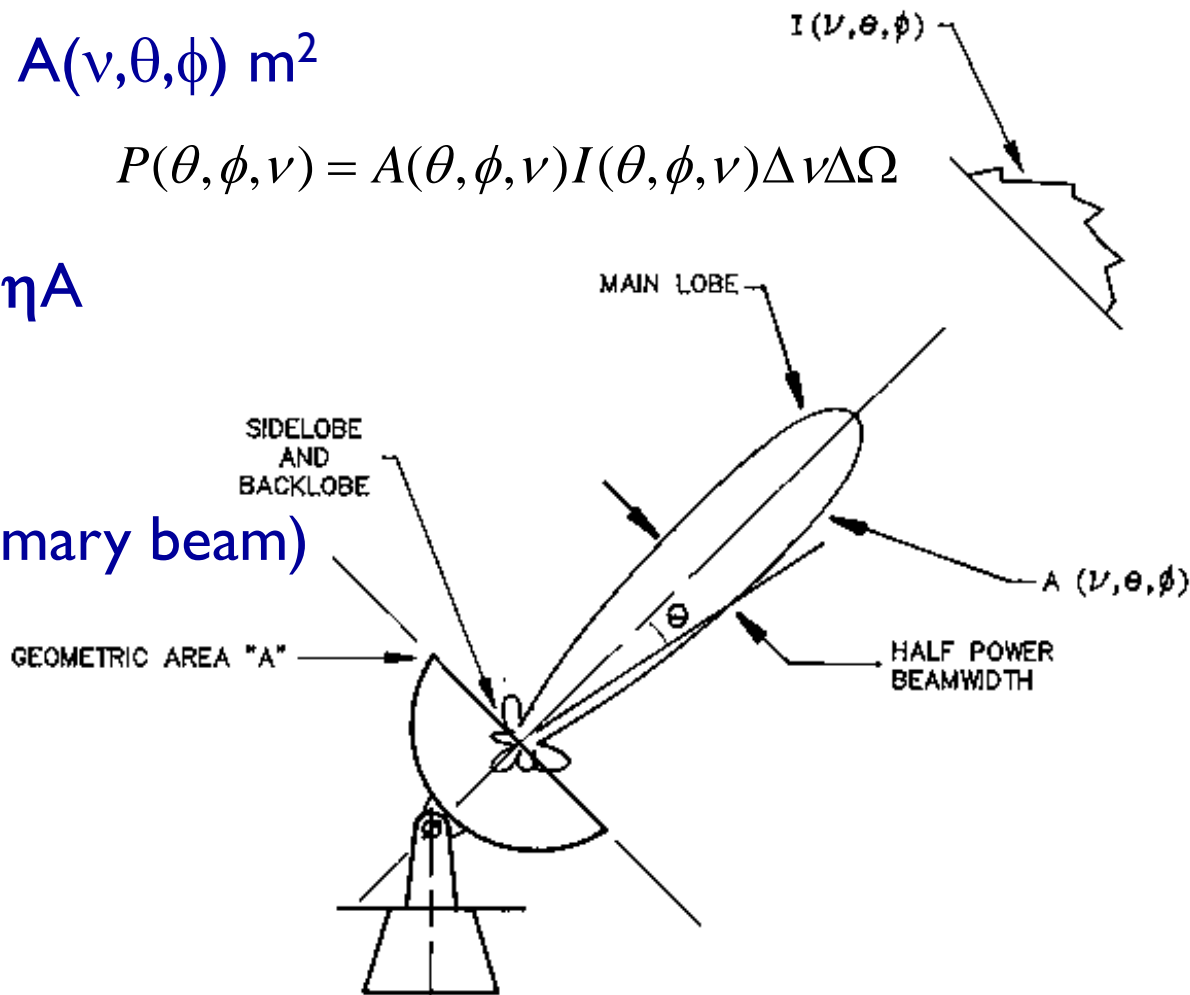η = aperture efficiency

Normalized pattern (primary beam)

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

Beam solid angle

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

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*)
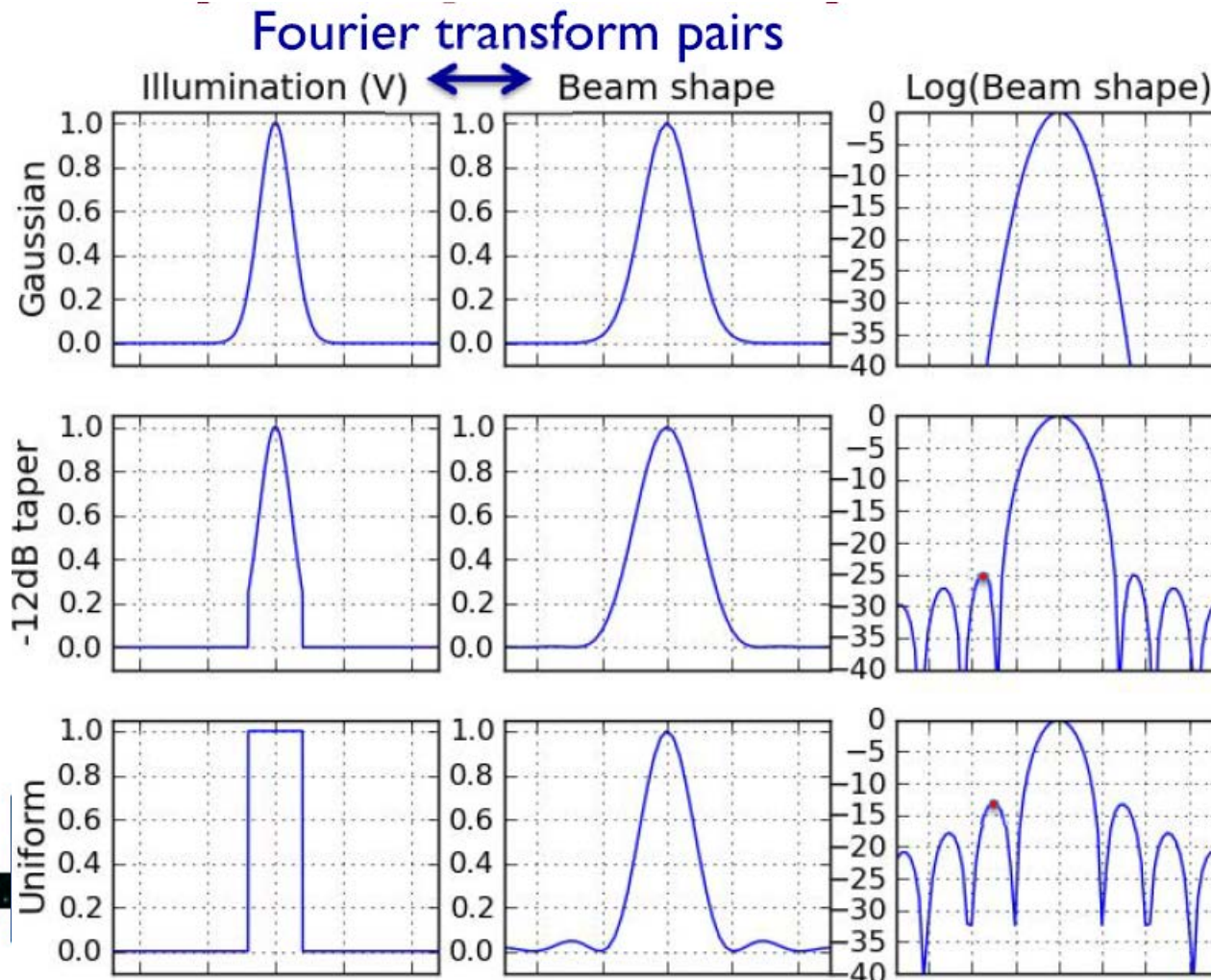
Credit: Hunter

$\theta_{3dB} = 1.02/D$
First null = 1.22/D
D = diameter in wavelengths
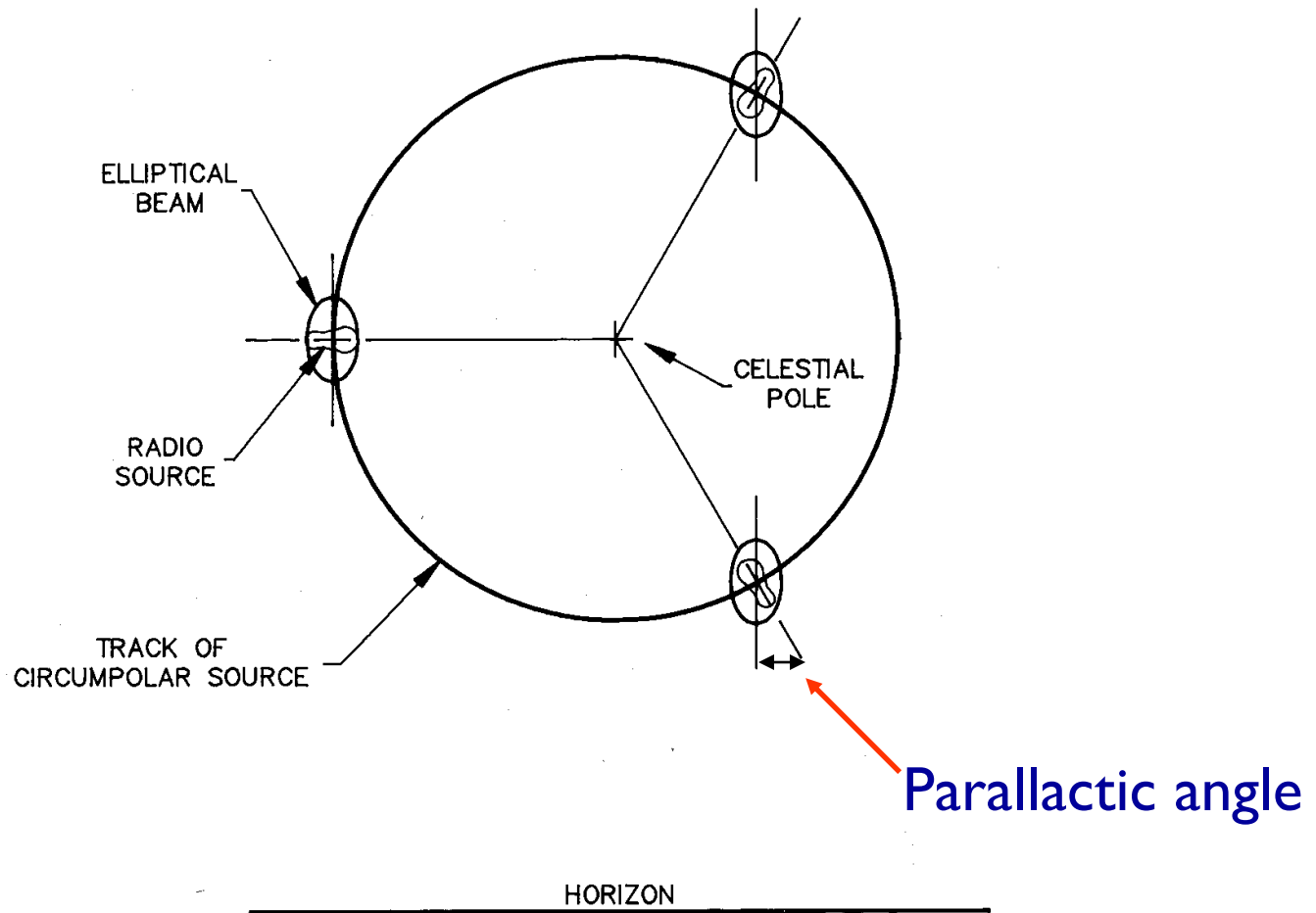
Antenna Mounts: Altitude over Azimuth

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

ELEVATION AXIS

AZIMUTH AXIS
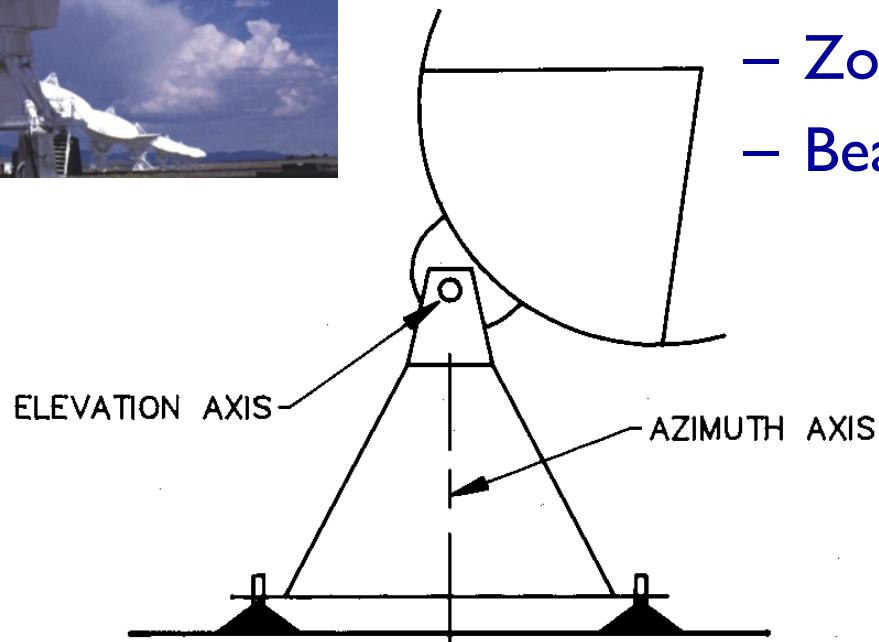
ALTITUDE OVER AZIMUTH MOUNT

Alt-Az: Beam Rotation on the Sky

ELLIPTICAL BEAM

RADIO SOURCE

TRACK OF CIRCUMPOLAR SOURCE

CELESTIAL POLE

Parallactic angle

HORIZON

Antenna Mounts: Equatorial

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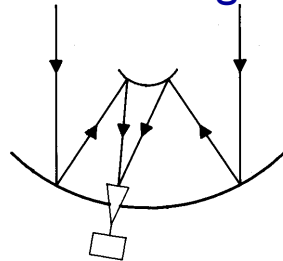 - Gravity performance
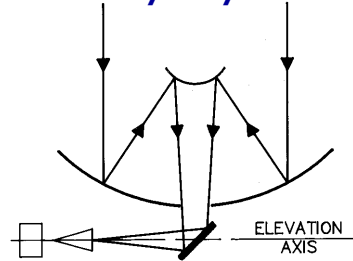 - Sources on horizon at pole

DECLINATION AXIS

POLAR AXIS

EQUATORIAL MOUNT
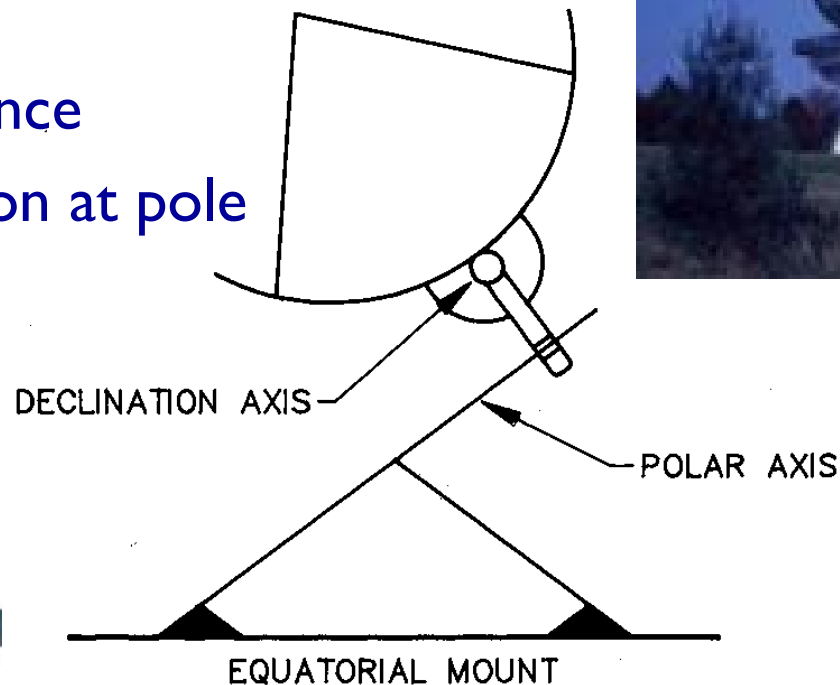
Antenna Optical Configurations
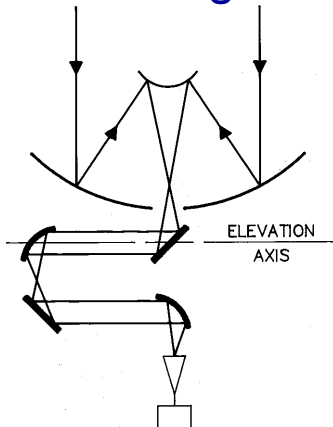

GMRT

VLA

NRO
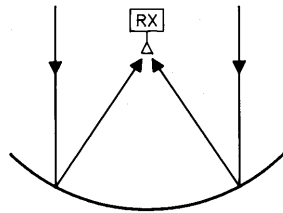
Prime Focus

Cassegrain
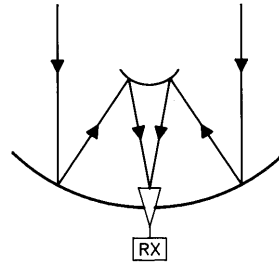
Offset Cassegrain
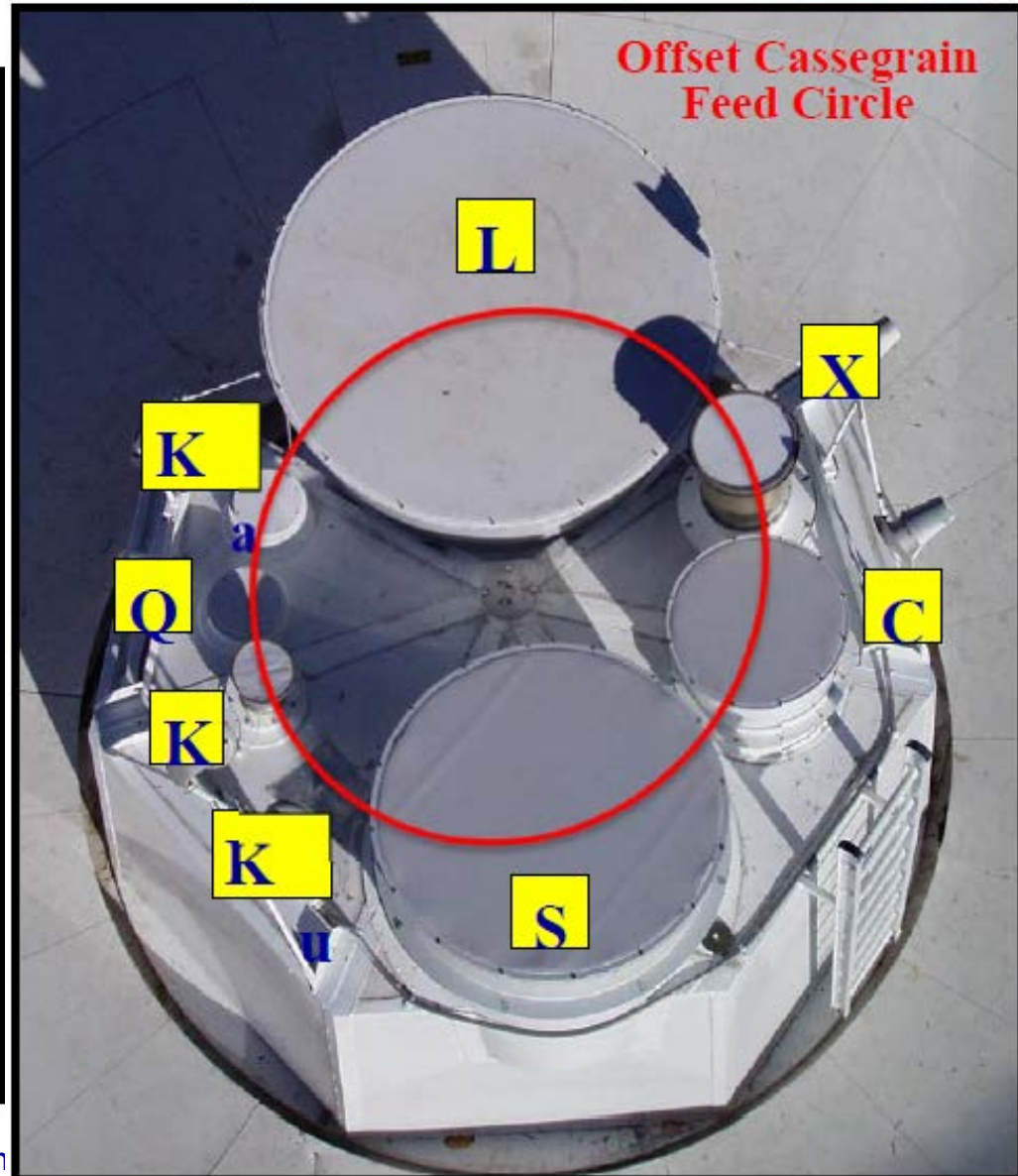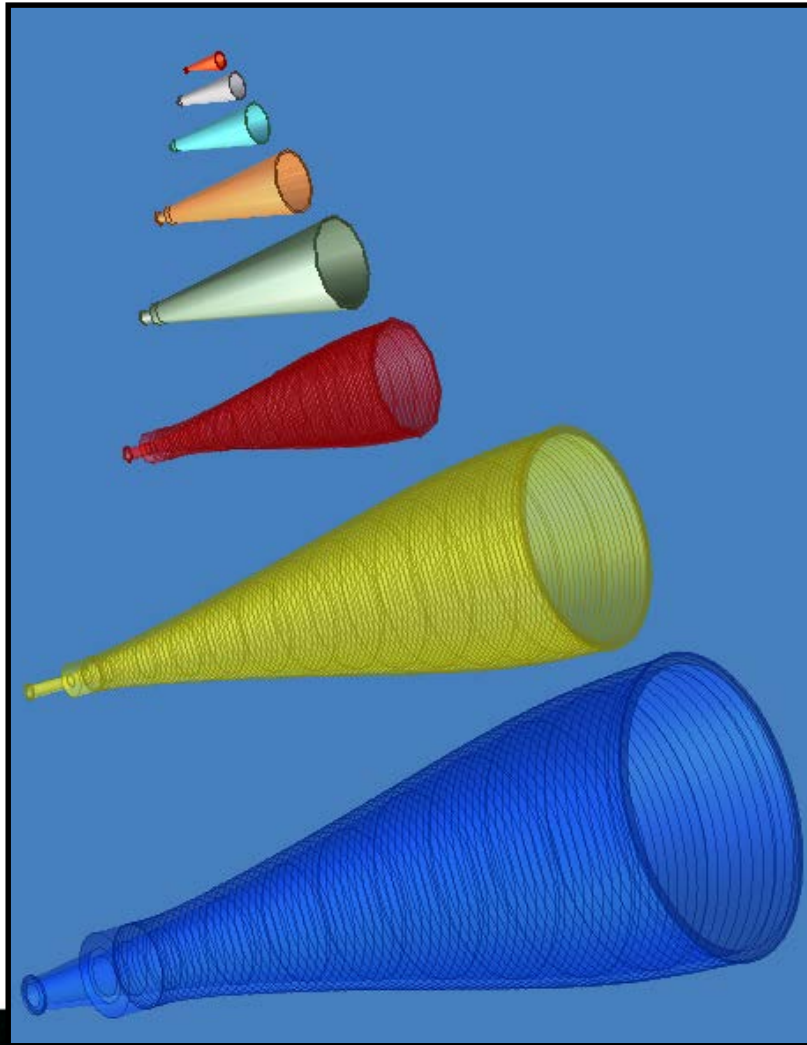
Naysmyth

Beam Waveguide

Dual Offset
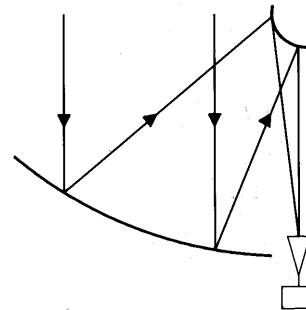
ATCA

CARMA

GBT

JVLA Feed Horns

Offset Cassegrain
Feed Circle

NRAO

16th Synth

Optical Configurations, Pros & Cons - 1

- 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

Optical Configurations, Pros & Cons - II

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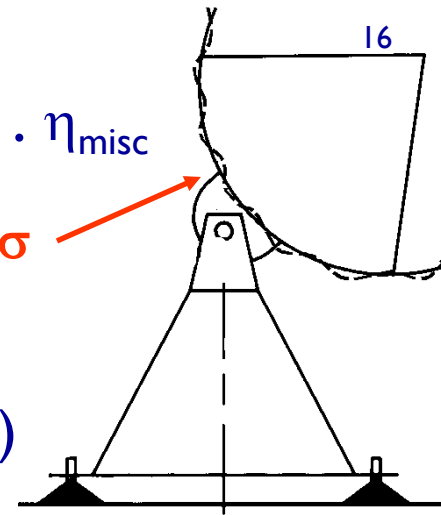 - Expensive panel tooling due to multiple panel sizes

Aperture Efficiency

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

rms error σ

η_{sf} = Reflector surface efficiency

Due to random imperfections in reflector surface

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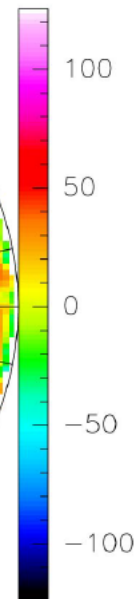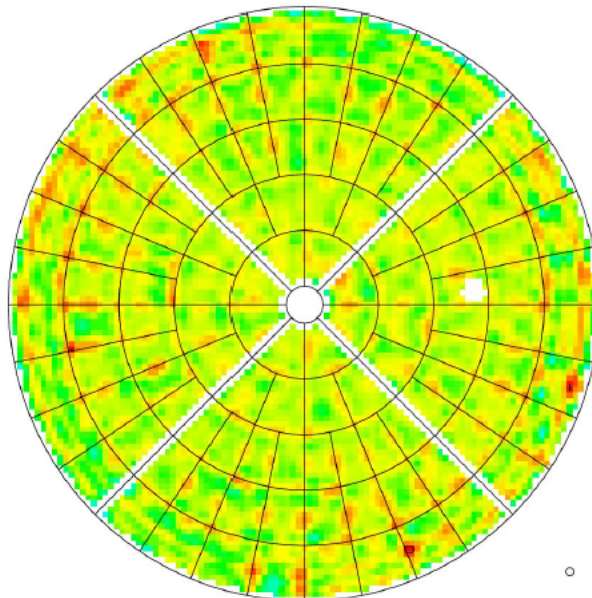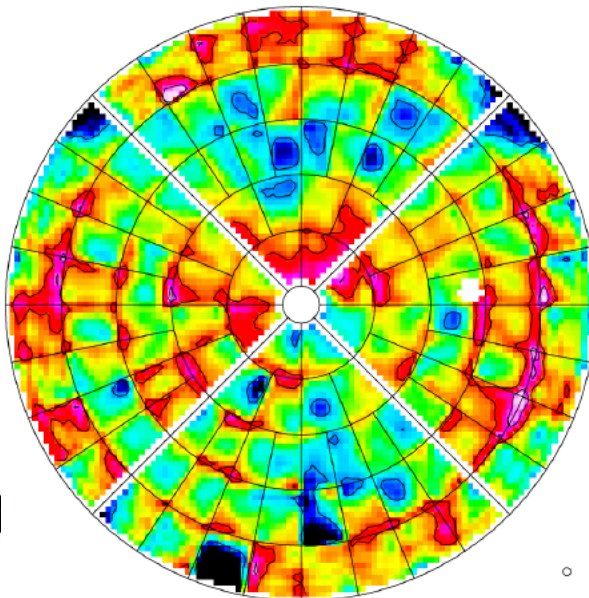
NRAO

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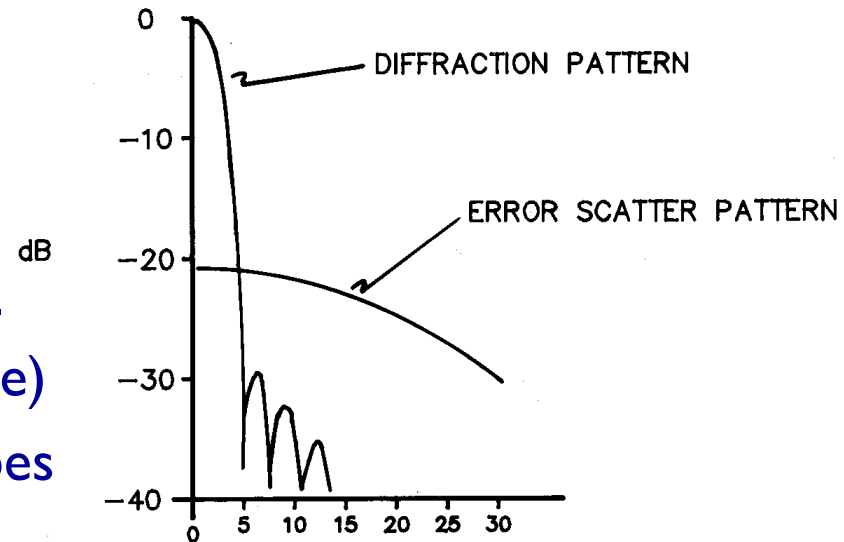
Before adjustment (43mm)   After adjustment (11mm)
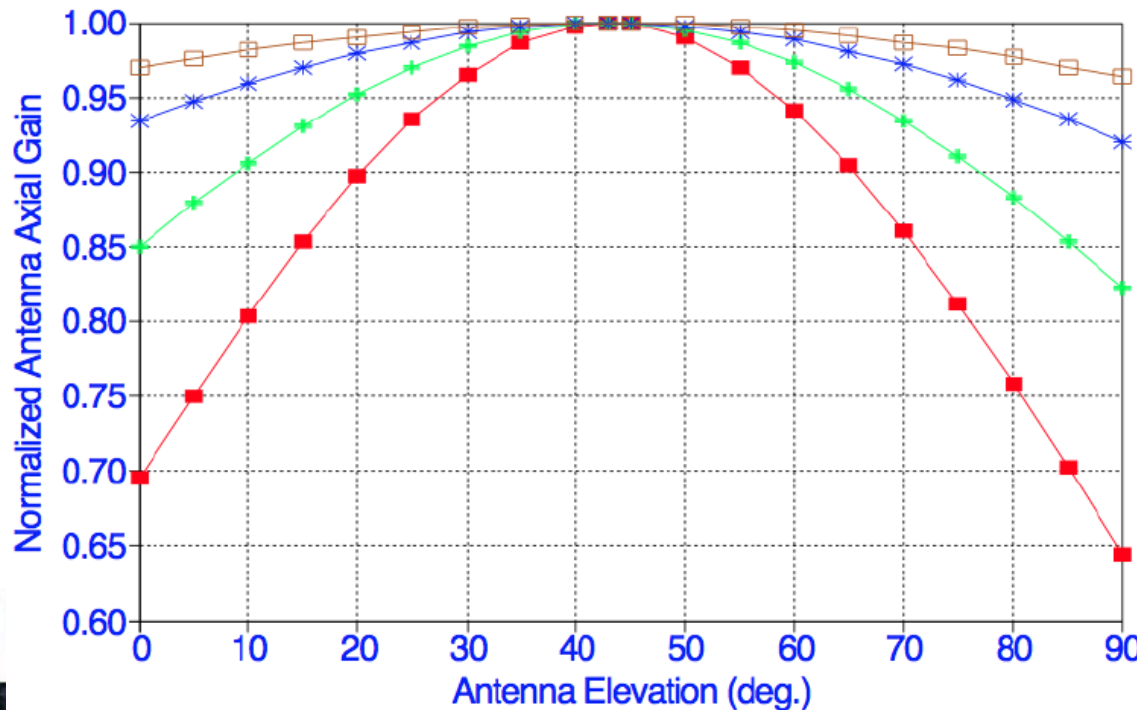

ALMA surface panel adjustment: phase map

Antenna Gain - I

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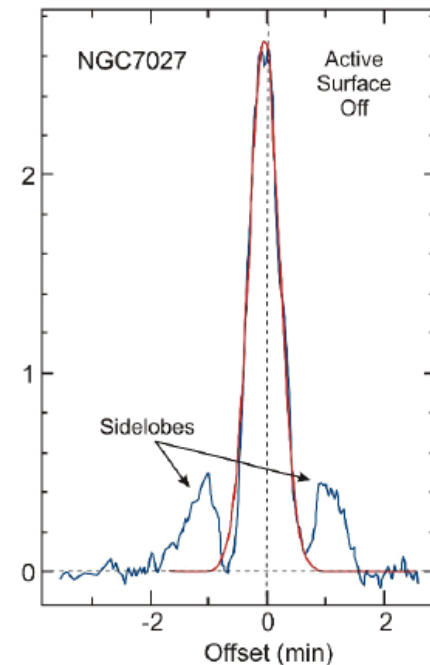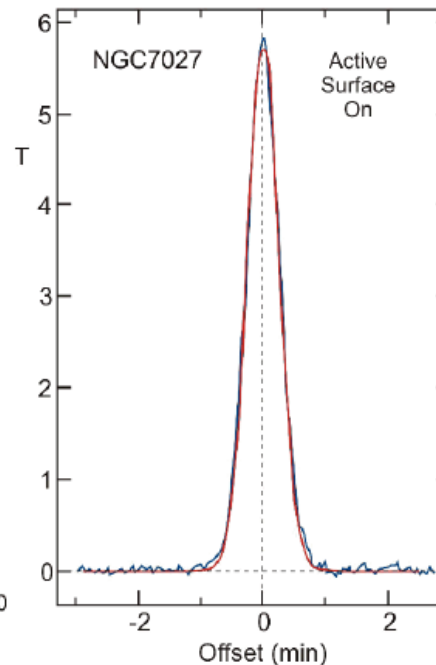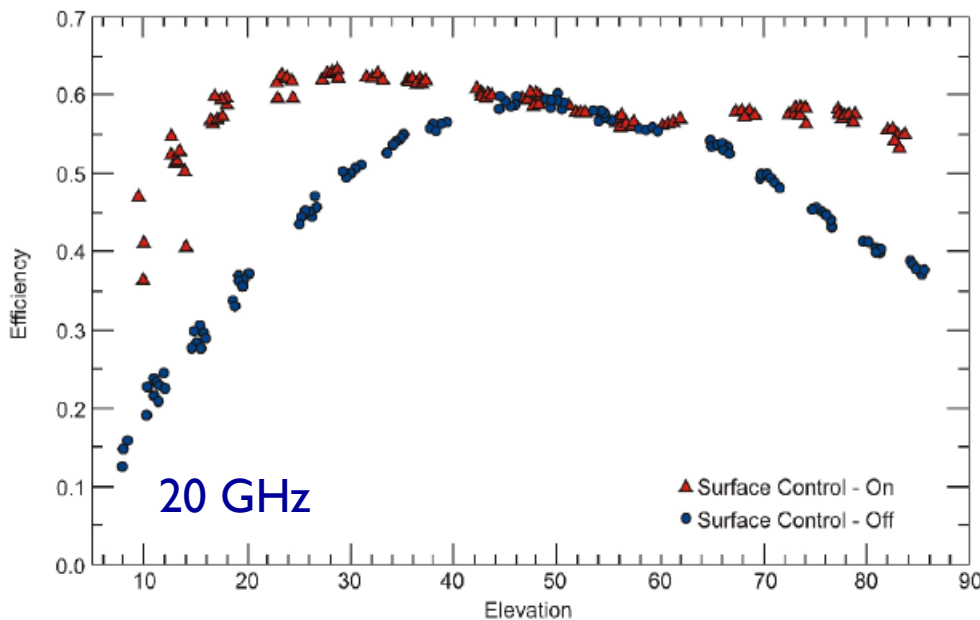

IRAM 30m (predicted, 1999)
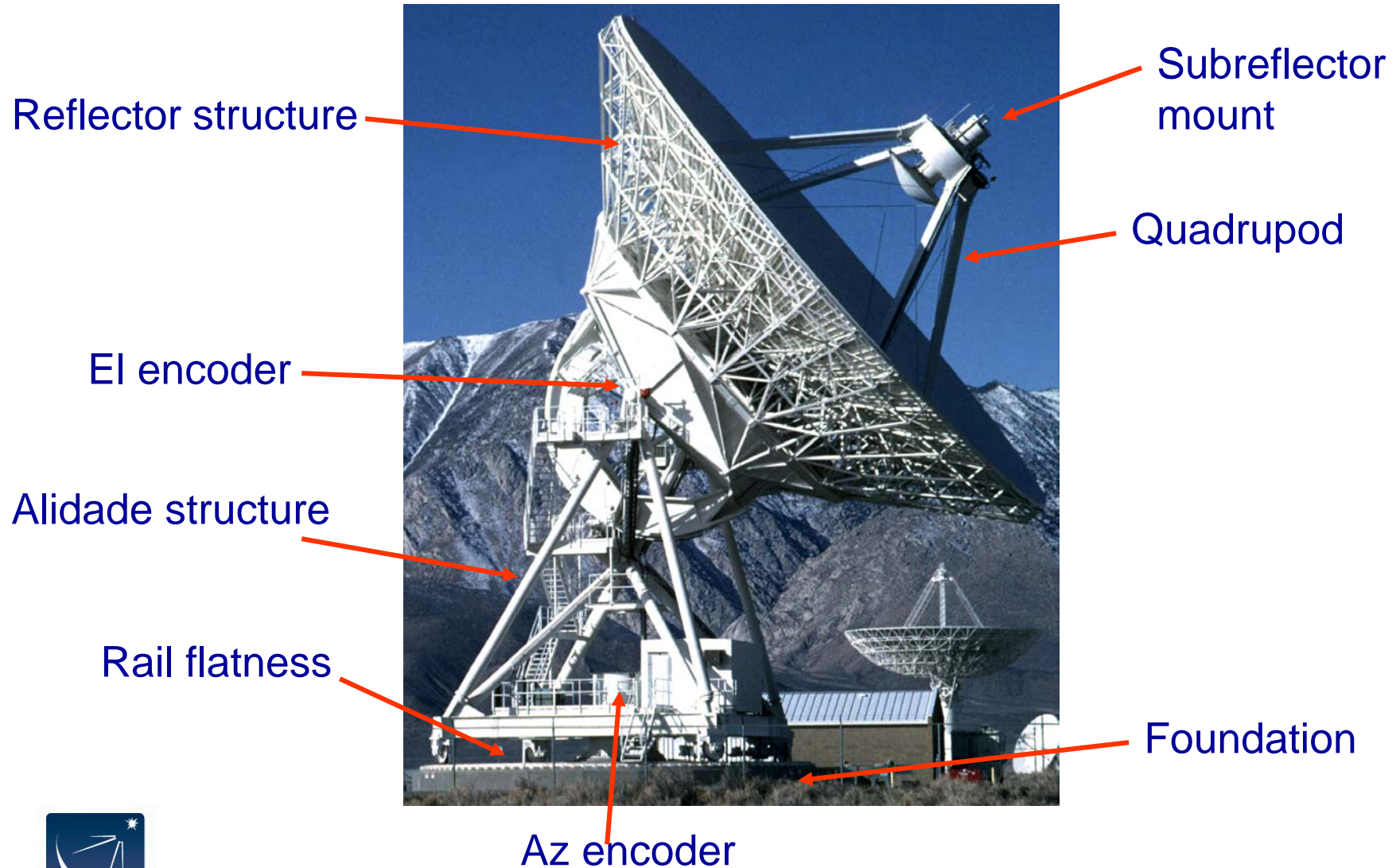
Gain Elevation Dependence

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

20 GHz

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
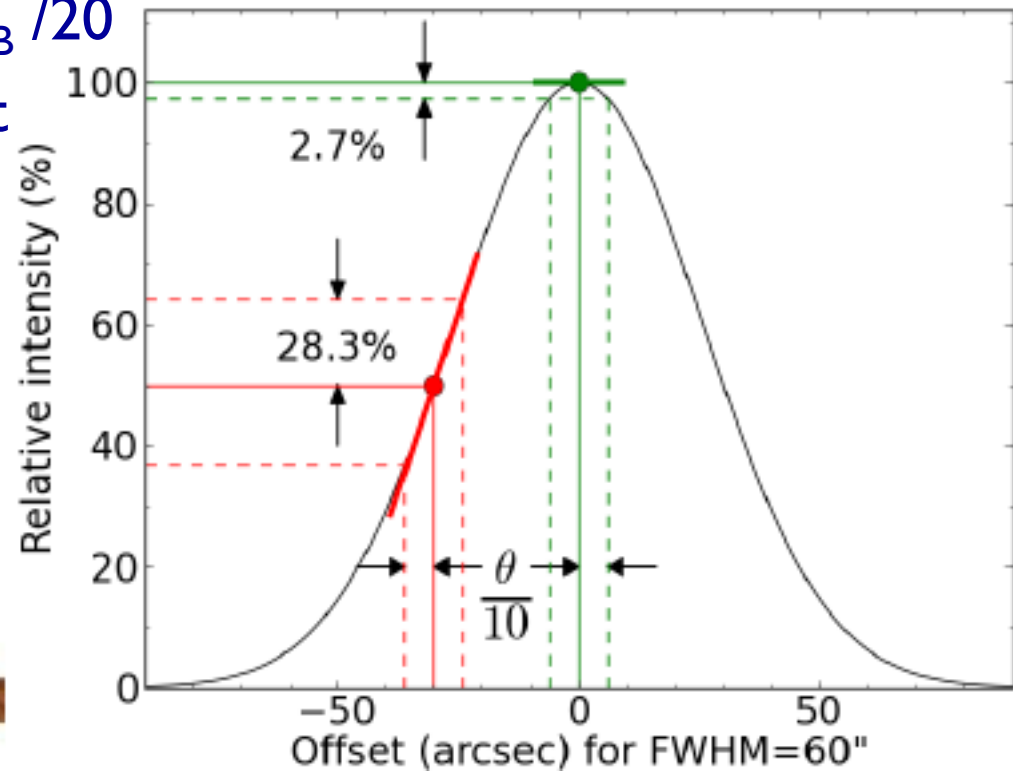
Antenna Polarization Properties

- 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)
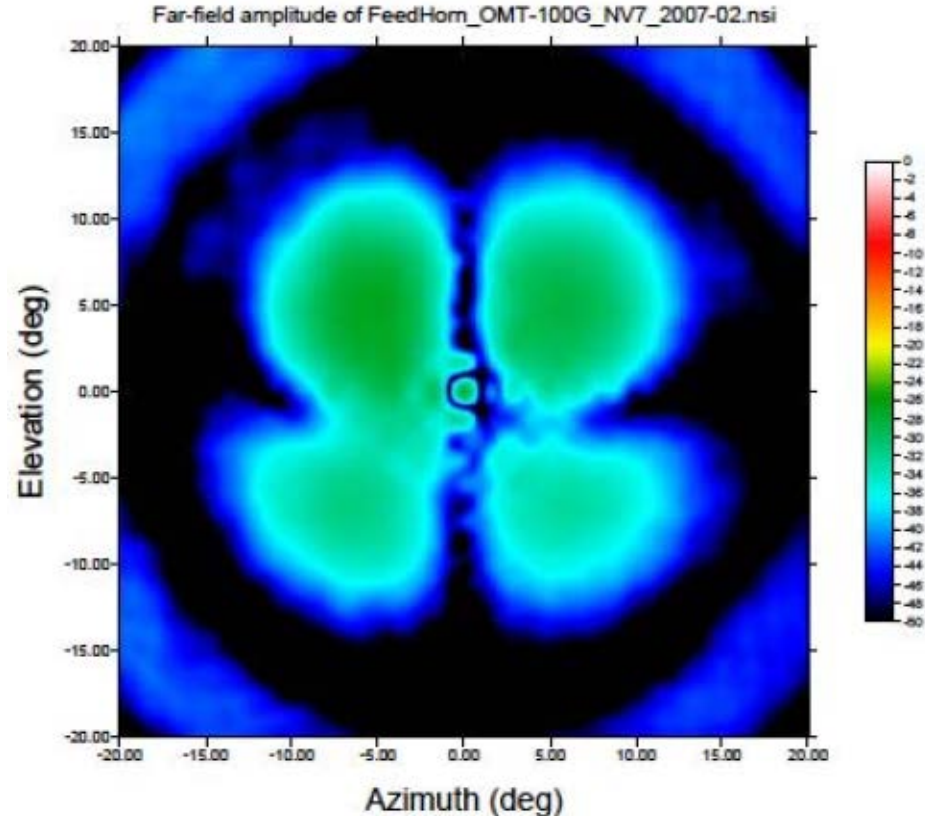
Polarization Beam Patterns
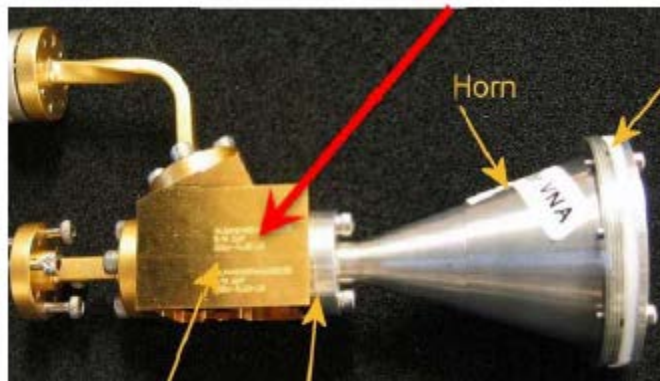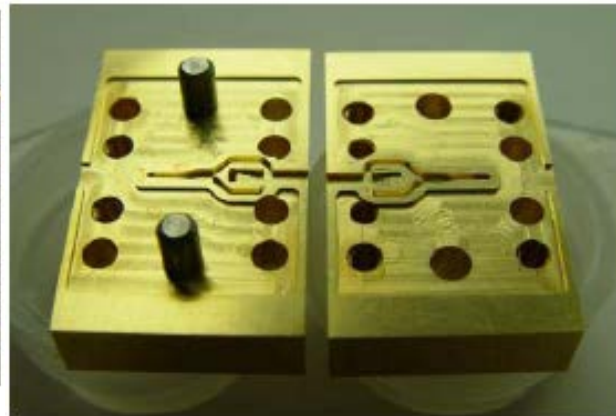
ALMA Band 3 (100GHz)
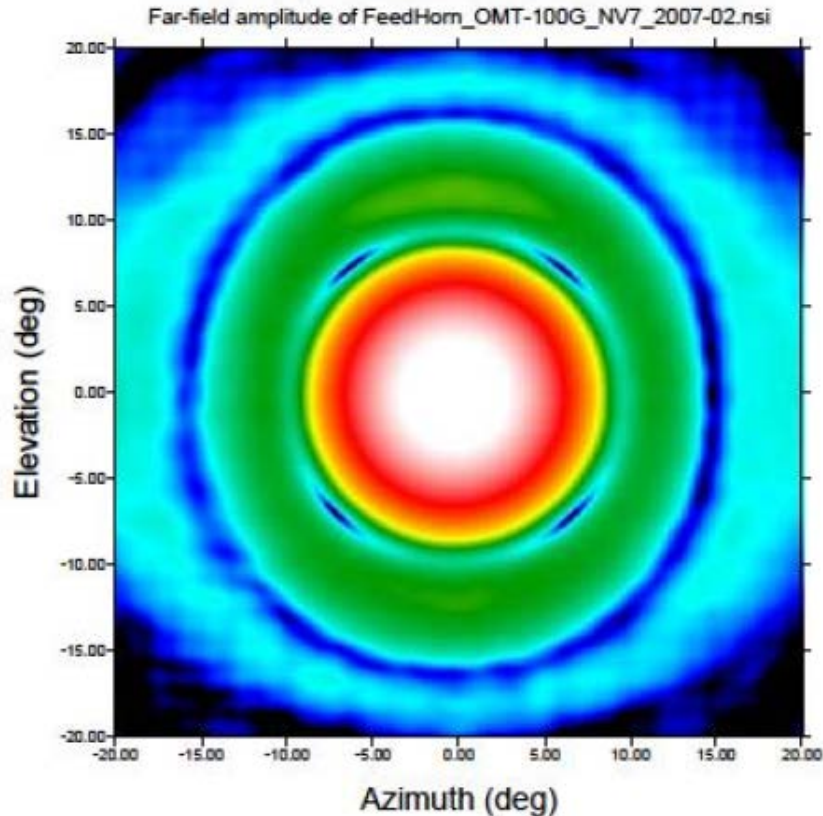
Co-polarization pattern

Cross-polarization pattern

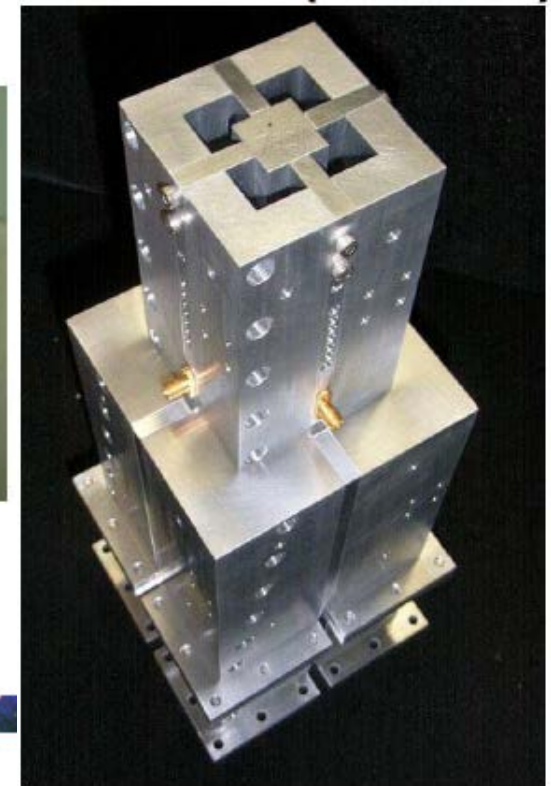# Front End Polarization Separation - I

- 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
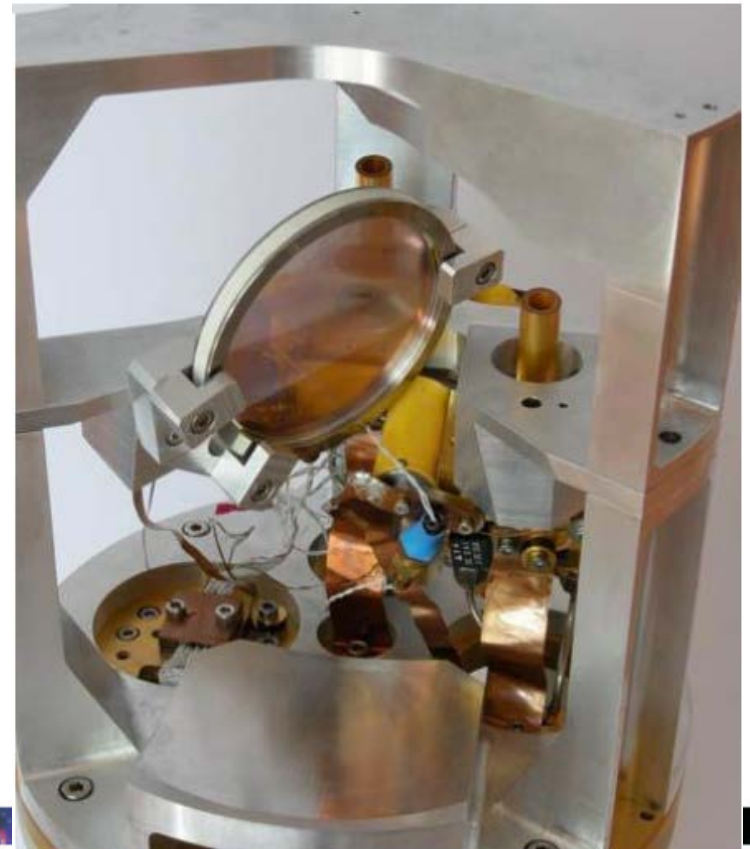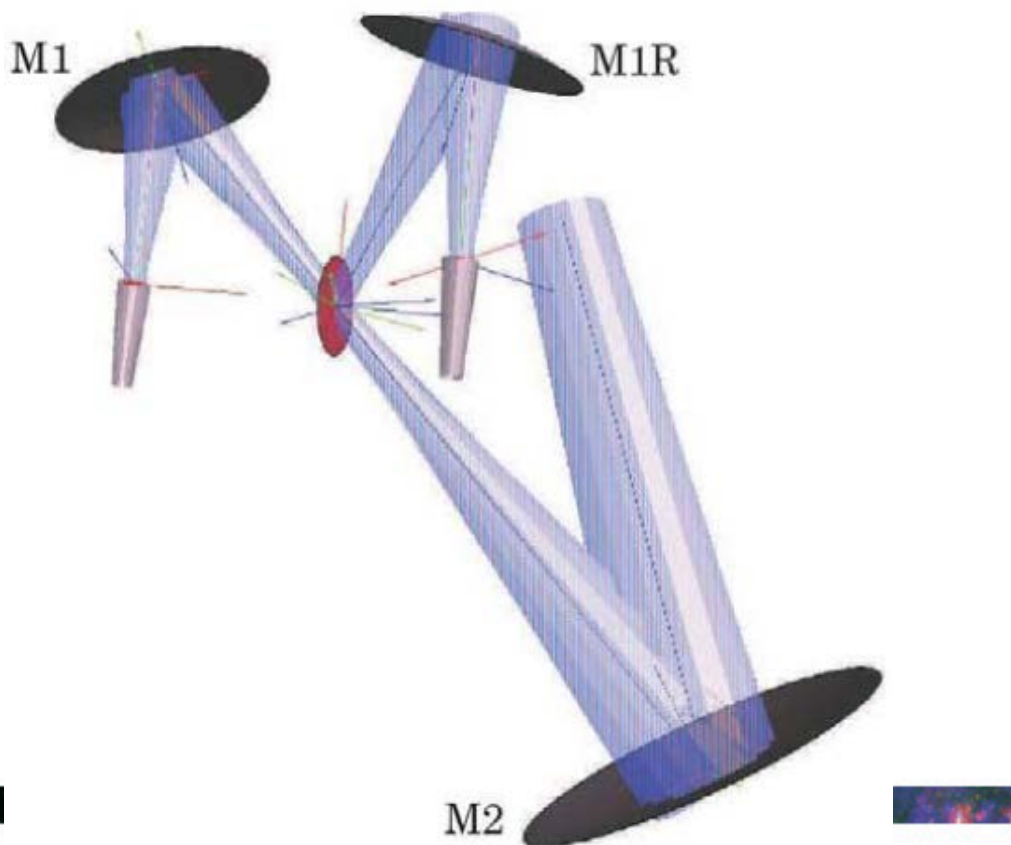

ALMA Band 3 OMT

ALMA Band 6 OMT

VLA S-band OMT

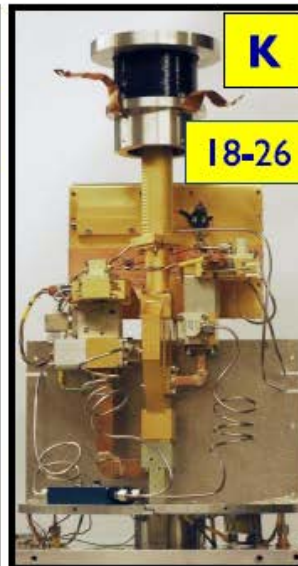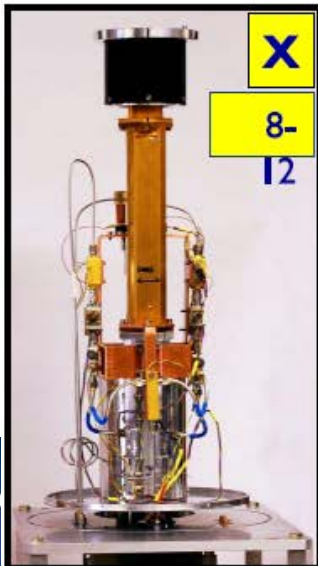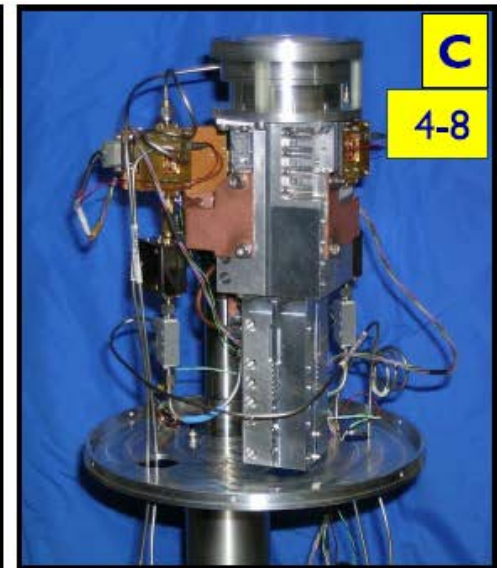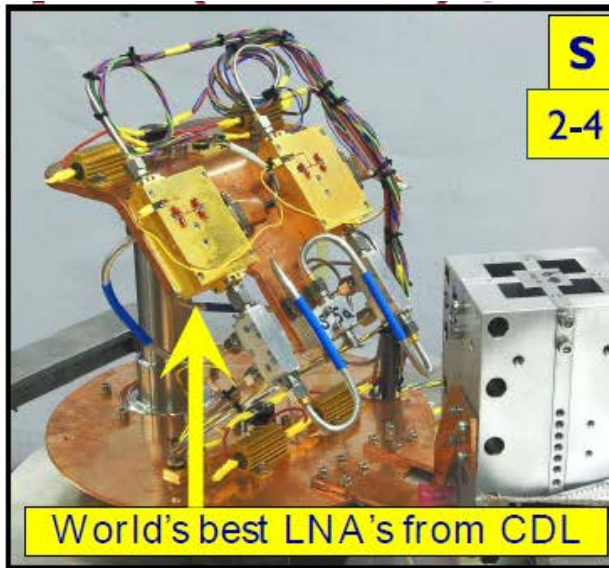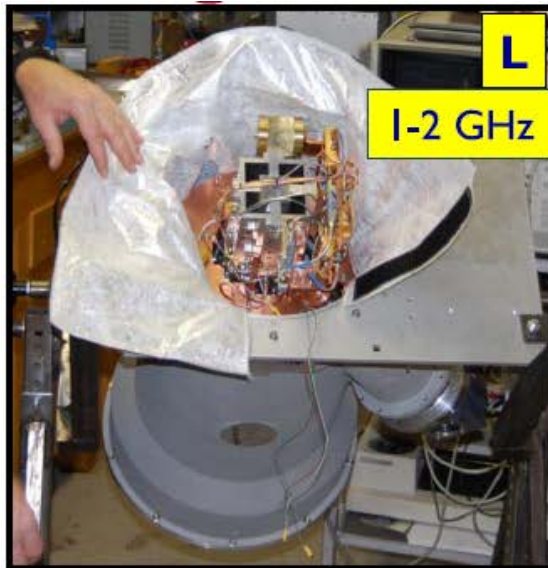# Front End Polarization Separation - II

- 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 — **Band 3** — 84-116
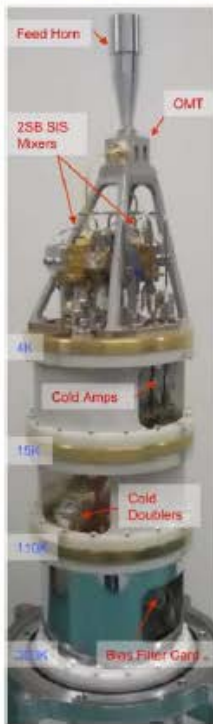
OMT — **Band 4** — 125-163

OMT — **Band 6** — 211-275
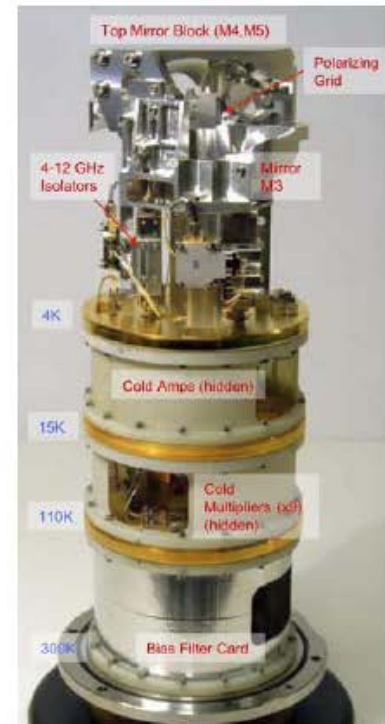
Wire grid — **Band 7** — 275-373
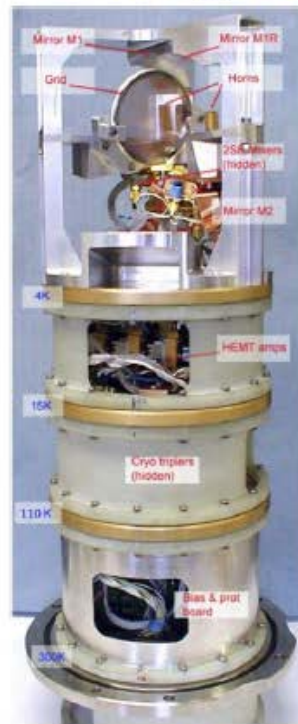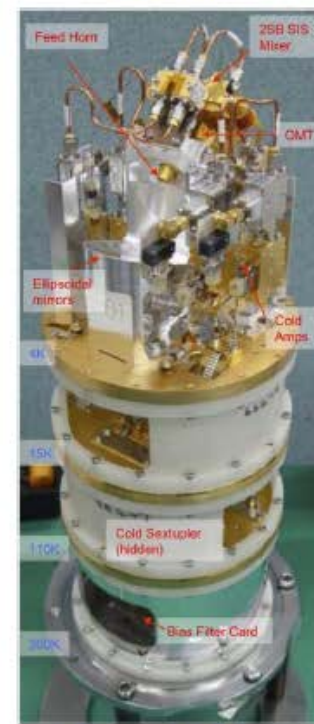
OMT — **Band 8** — 385-500

Wire grid — **Band 9** — 600-720 GHz

Receivers are dual linear polarization

credit: Hunter

ALMA Front End Cryostat
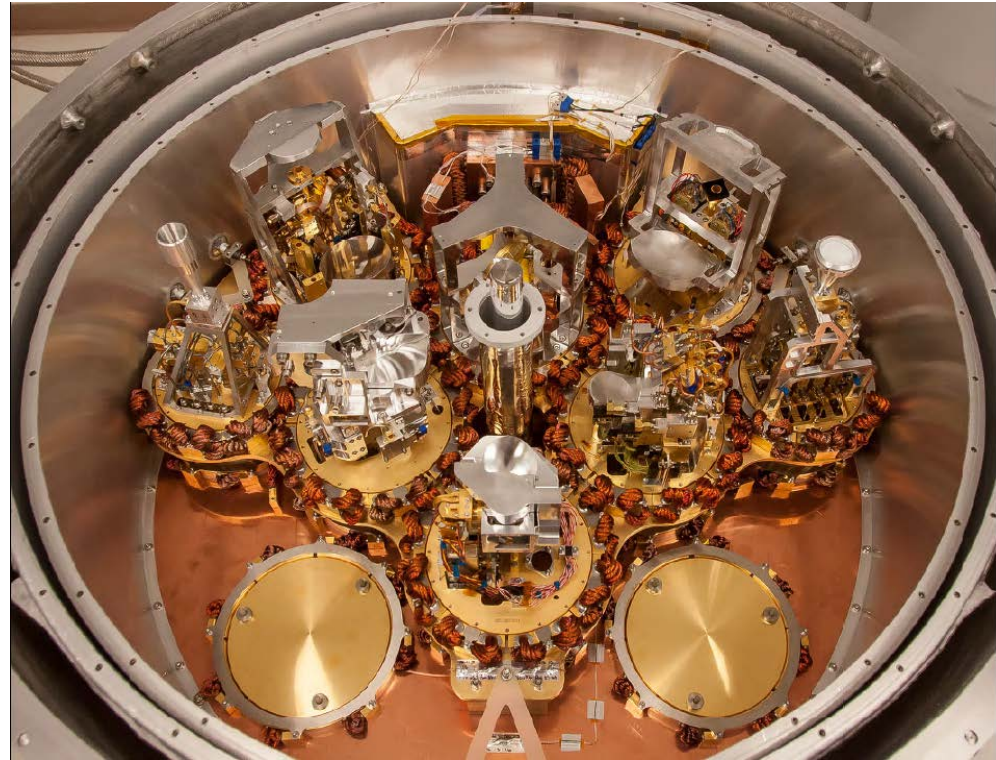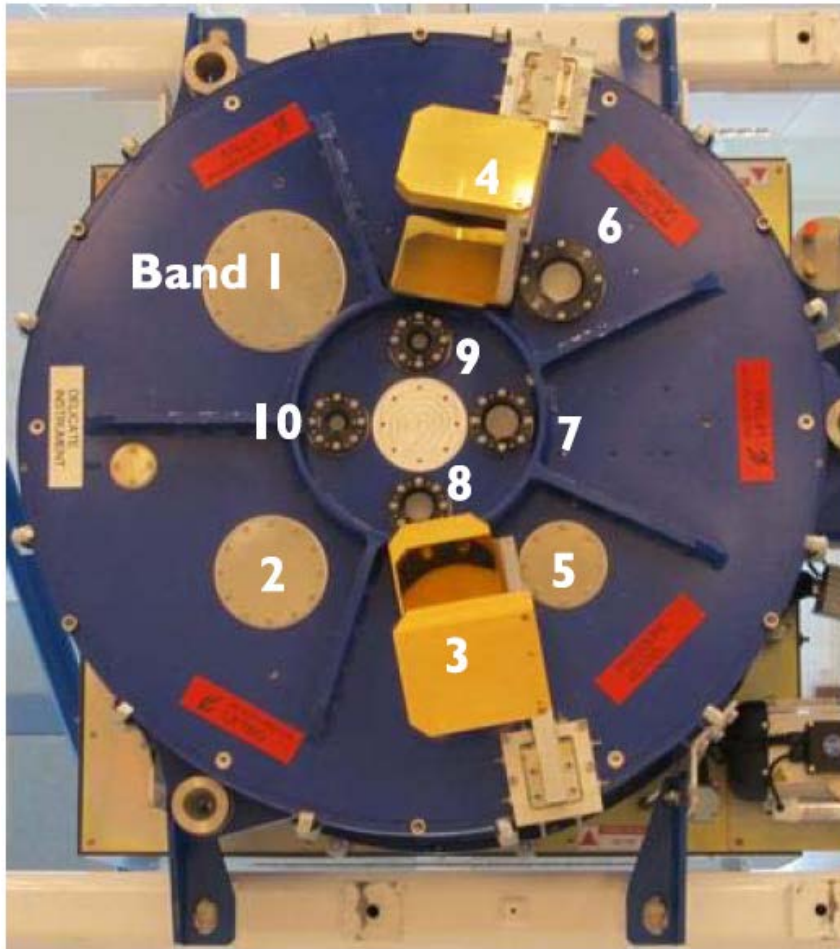
Receivers: Noise Temperature

- 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

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

  k_B = Boltzman's constant ($1.38*10^{-23}$ J/$^{\circ}$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

EVLA Sensitivities

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

S = source flux (Jy)

SEFD = system equivalent flux density

SEFD = Tsys/K (Jy)

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

JVLA Receiver Performance

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

Simple T(Rx) Noise Model
$$T(Rx) = m \cdot F + b$$
where $m = 1°K / GHz$, $b = 8°K$ for $1 \rightarrow 4$ GHz
where $m = 0.5°K / GHz$, $b = 2°K$ for $4 \rightarrow 50$ GHz
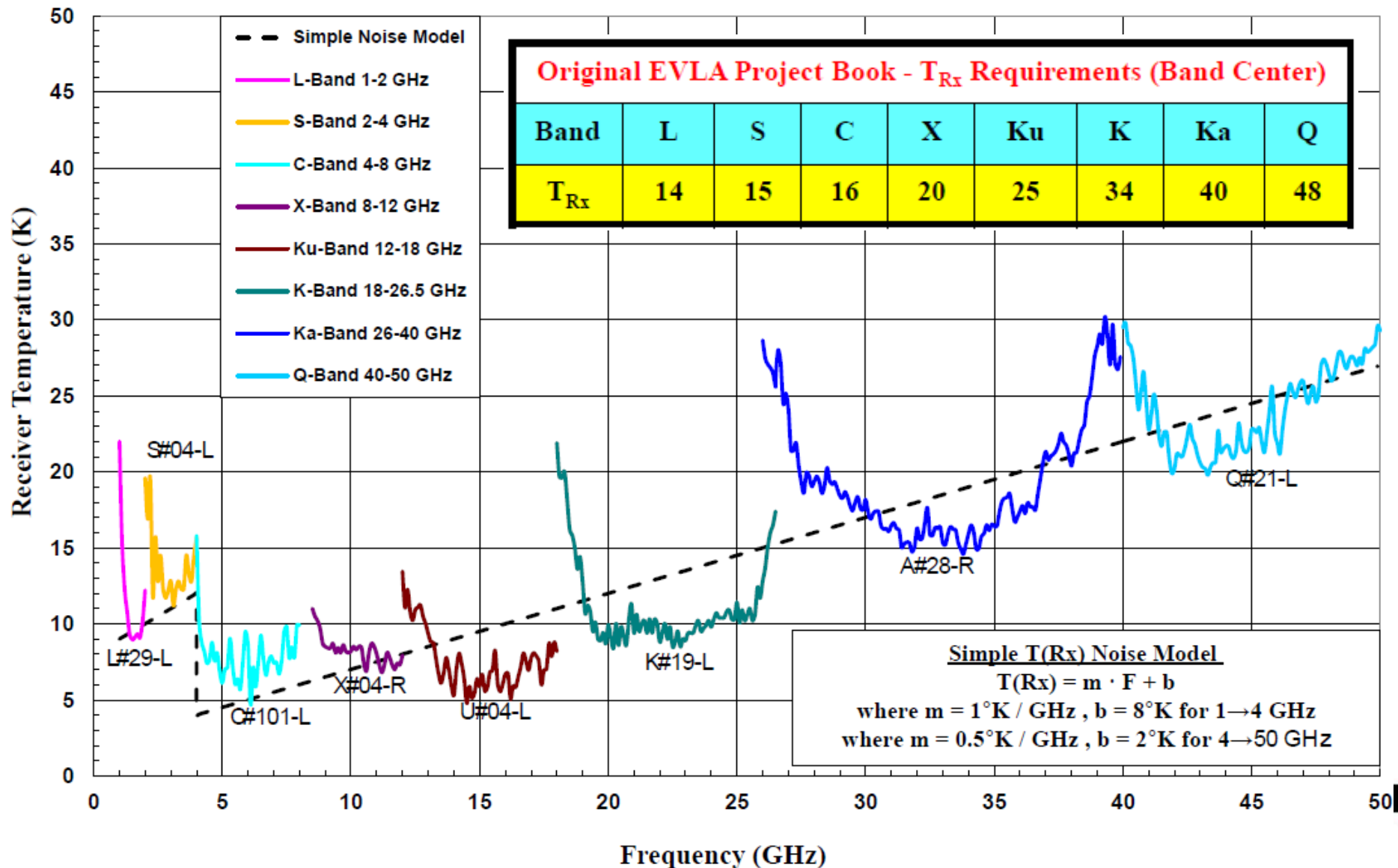
Additional Information

- 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