Antennas and Receivers

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Outline: Following the Signal Path

- **Antennas:**
  - Shapes, efficiencies, primary beam response, holography
  - Pointing, tracking, and servo systems
  - Polarization
- **Receivers:**
  - **Amplifiers & Mixers**
  - **Local oscillators**
    - Phase lock loop
    - Modulation (Walsh functions and sideband separation)
  - **Sensitivity**
    - Receiver temperature
    - Derivation of radiometer equation

Role of an antenna

- Track and capture radiation from an object over a broad collecting area and efficiently couple it into a receiver so that it can be detected, digitized, and analyzed.
- Example:
  - 100m GBT operating at 90GHz
  - WR-10 waveguide: 2.54 mm
  - Physical reduction: 40000x

An aside: What the heck is a dB (decibel)?

- Expression of the relative strength of two signals
  - A change of 3dB = 2x   (-3dB = 0.5x)
  - A change of 10dB = 10x   (-10dB = 0.1x)
  - A change of 20dB = 100x   (-20dB = 0.01x)

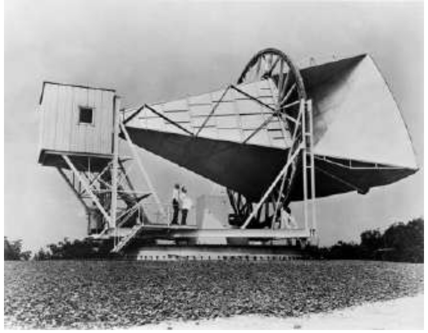
Importance of Antenna properties on your data

- Antenna amplitude and phase patterns cause amplitude and phase to vary across the field of view.
- Polarization properties of the antenna modify the apparent polarization of the source.
- Antenna pointing errors 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 shapes

- **Horn antennas**
  - Advantage: Broad bandwidth
  - Large apertures not practical, (long, cannot be close-packed)
- **Reflector dish antennas**
  - Advantage: large apertures, homology (von Hoerner 1967)
  - Disadvantage: Require many feeds, each of limited bandwidth
- **Dipole (wire) antennas**
  - Examples: LWA, LOFAR low-band
  - Advantage: wide field, beam-forming
  - Disadvantage: low gain, need 1000s

Purcell horn: HI (1951)



Crawford Hill horn reflector: CMB (1965)

VLA

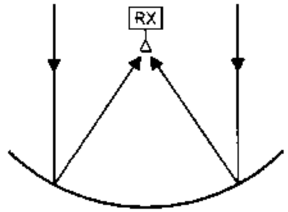
GBT feeds

LWA antenna

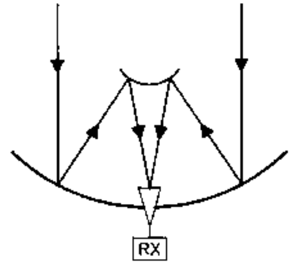
Reflector antennas

GMRT

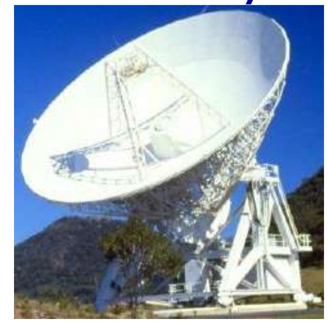
Prime Focus



On-axis Cassegrain



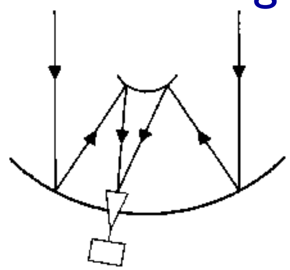
(best for array receivers)



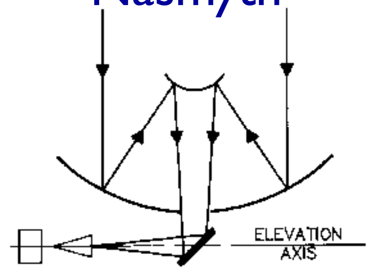
ATCA, Mopra

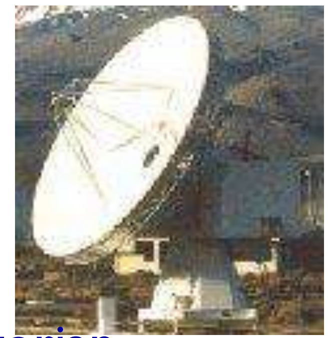
VLA, ALMA

Offset Cassegrain



Nasmyth

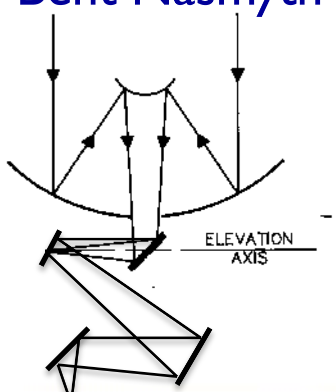




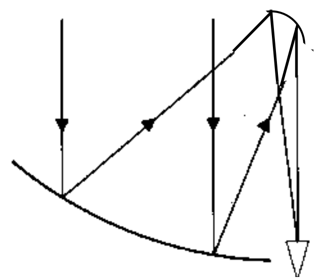
CARMA, CSO

SMA

Bent Nasmyth



Dual offset Gregorian

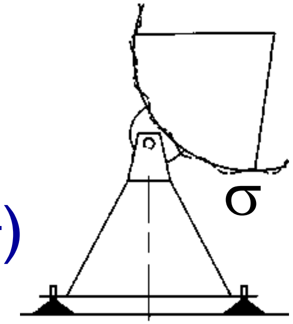


GBT

Receivers do not tilt in elev.

Cleanest beam, minimizes standing waves, polarization asymmetry compensated -- Mizugutch et al. (1976)

Reflector antenna efficiencies



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

Effective area (on-axis): $A_0 = \eta A =$ (aperture efficiency)(πR^2)

where $\eta = \eta_{surface}\eta_{blockage}\eta_{spillover}\eta_{taper}\eta_{radiation}\eta_{misc}$

$\eta_{surface} = \exp(-(4\pi\sigma/\lambda)^2)$ σ = rms surface error (Ruze 1966)

$= 0.44$ for $\sigma = \lambda/14$ (VLA at 43 GHz) $\sigma_{VLA} \sim 500\mu m$

$= 0.79$ for $\sigma = \lambda/26$ (VLA at 22 GHz) $\sigma_{ALMA} \sim 25\mu m$

$\eta_{blockage}$ = blockage efficiency (feed legs and subreflector)

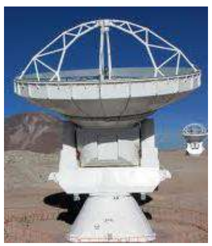
$\left.\begin{array}{l}\eta_{spillover} = \text{feed spillover efficiency} \\ \eta_{taper} = \text{feed taper efficiency}\end{array}\right\} \eta_{illumination} = 0.8$ for -10dB taper

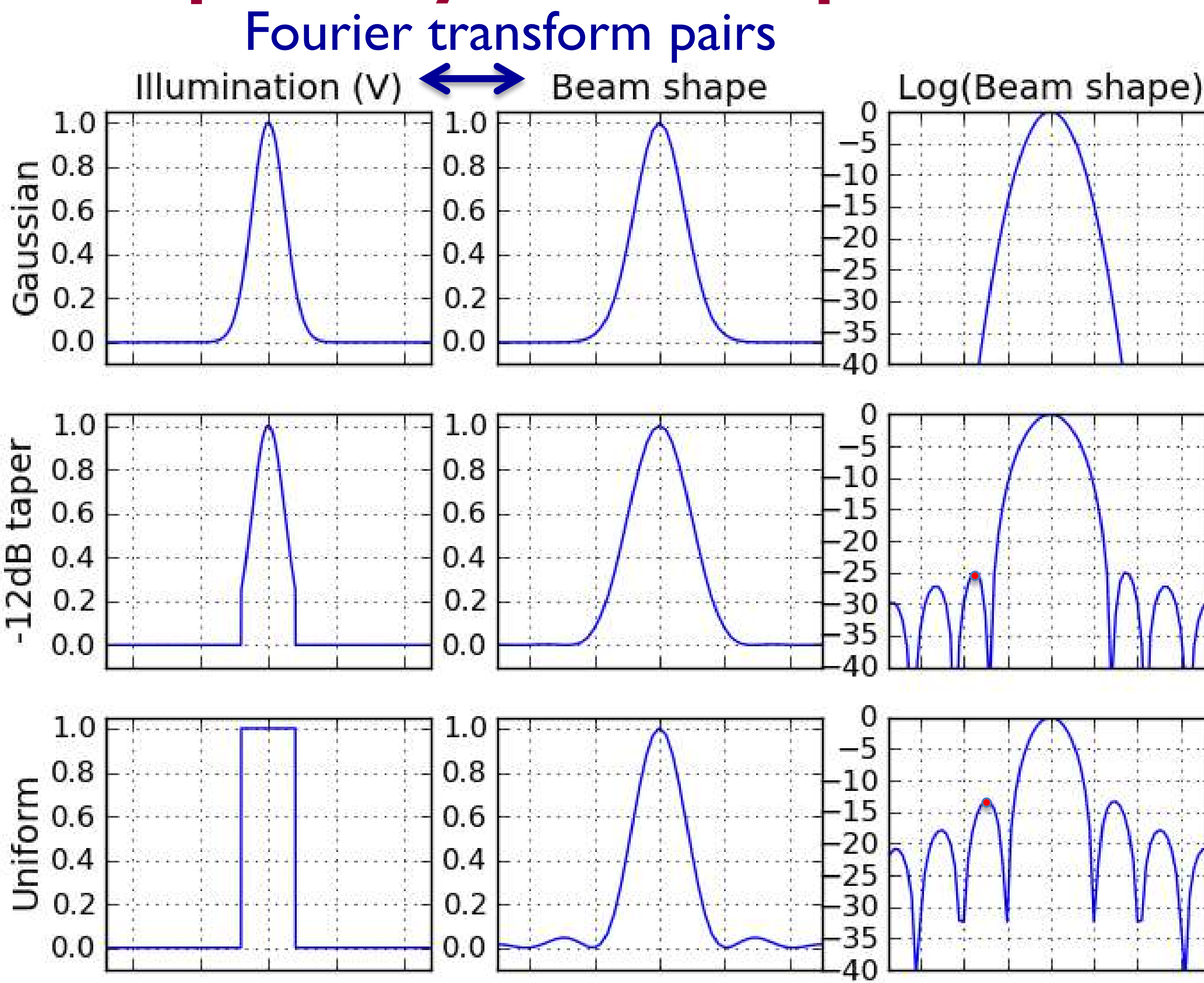
$\eta_{radiation}$ = metal reflection efficiency (~0.99 per Al mirror)

η_{misc} = diffraction, phase, focus error, polarization efficiencies

Comparison of primary beam response

Set by the illumination taper of the receiver feed,
i.e how much of the outer part of the dish are we using?





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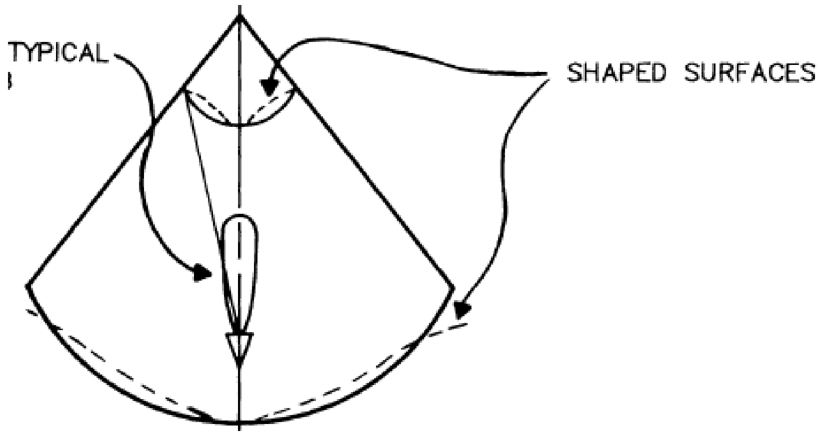
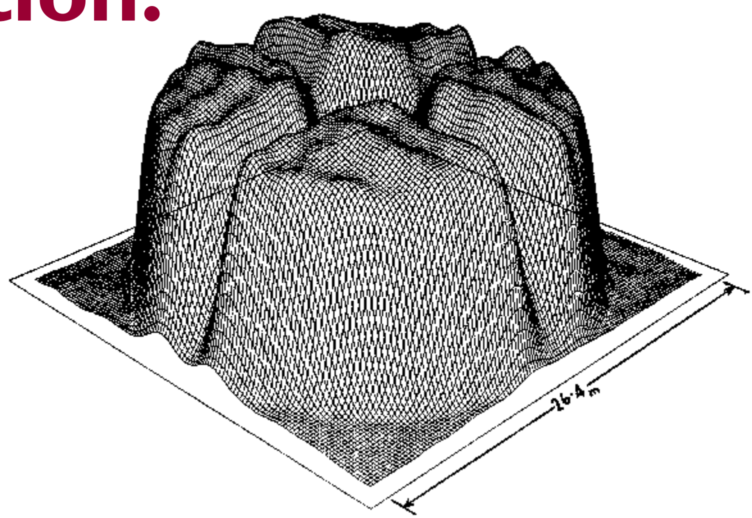
Uniform Antenna illumination: VLA



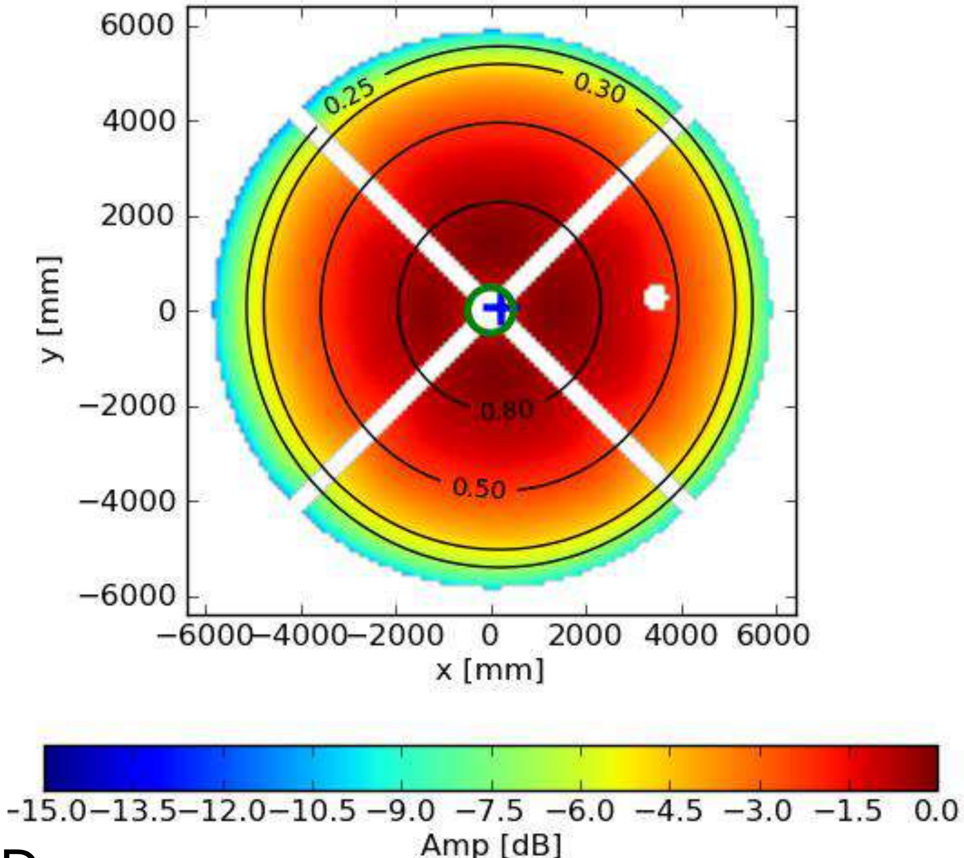


- Shaped symmetric primary, shaped *asymmetric* secondary
- Close to Airy disk (FWHM~1.028 λ/D)
  (radius of 1st null=1.22 λ/D)
- Better illumination efficiency (90%) at expense of higher sidelobes (-16 dB)
- CASA model: Airy truncated at 10%

Tapered Antenna illumination: ALMA

also SMA, CARMA, etc.

- Paraboloidal primary
- Hyperboloidal secondary
- -10dB taper: good compromise between efficiency and sidelobes
- Illumination efficiency ~ 80%
- Low sidelobes (-23 dB)
- Larger beam: $\theta_{FWHM} = 1.13\ \lambda/D$
- Baars* (2007) and ALMA Memo 456 give numerical formulas relating FWHM to taper:



$\tau = 10\text{\^{}}(\text{taper}/20)$

$\theta_{FWHM}=(1.243 - 0.343\tau + 0.12\tau^2)\ \lambda/D$

**The Paraboloidal Reflector Antenna in Radio Astronomy and Communication*

Holography is a vital tool

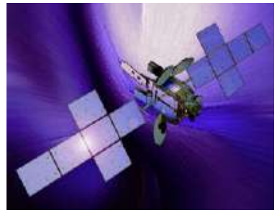
The technique of imaging the (complex) beam pattern of an antenna and Fourier transforming back to the antenna surface illumination (aperture plane) is known as "holography". (Napier & Bates 1971, Bennett et al. 1976).

1. Interferometric holography is done with a beacon transmitter on a tower, or on a satellite, but can also be done on bright quasars, which is called "astroholography" or "celestial holography".
2. Non-interferometric holography, also called "out-of-focus (OOF)" or "phase retrieval", is useful for measuring large-scale surface error

Holography allows us to measure:

1. Antenna panel misalignment (e.g. ALMA: Baars et al. 2007, IEEE A&PM)
2. Systematic antenna panel mold error (GBT: Hunter et al. 2011, PASP)
3. Large-scale error due to thermal effects (GBT: Nikolic et al. 2007, A&A)
4. Illumination pattern alignment errors (see ALMA Memo 402)
5. Effect of feed legs on the beam

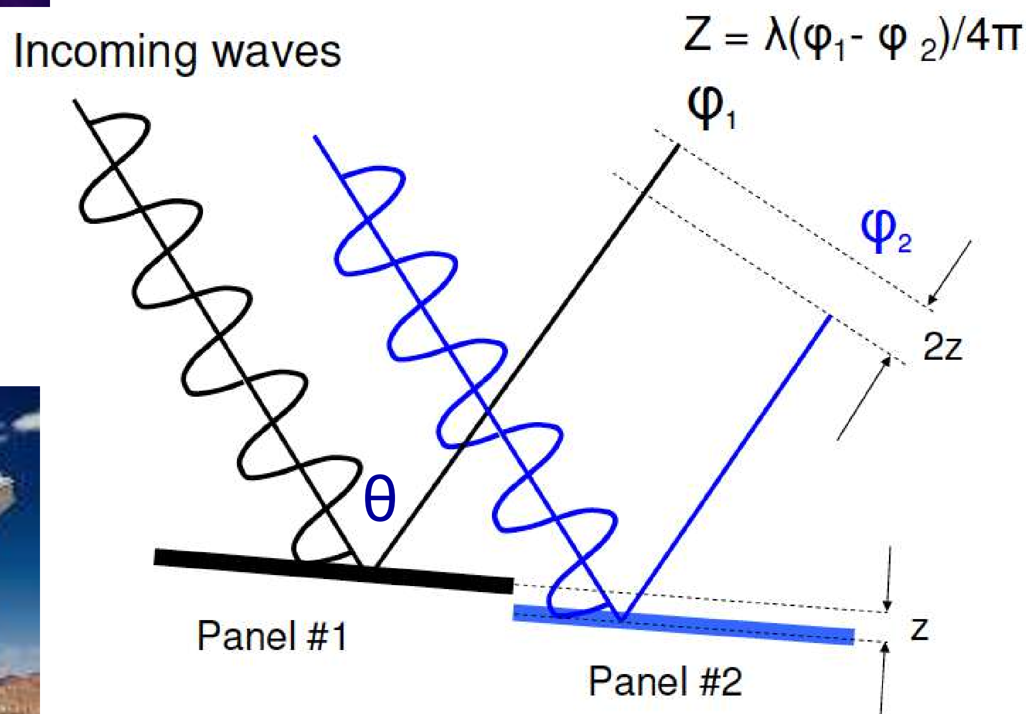
Holography principle



Record a 2D image of complex voltage pattern $V(\theta, \theta')$

Antenna(s) under test

Reference antenna



$$V(\theta,\theta') = \sum_{x,y} \exp[i(\psi_x(\theta,\theta') - \psi_y(\theta,\theta'))]$$

What do holography data look like?

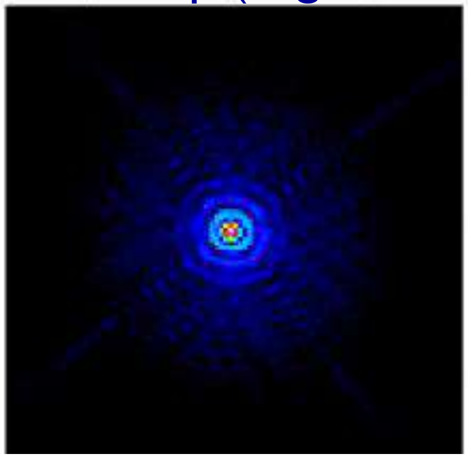
Beam map (angle units)

Example:

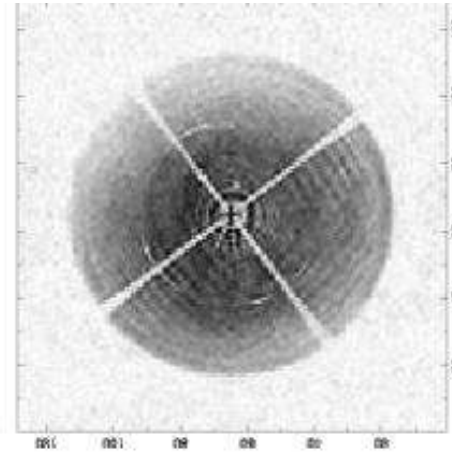
SMA at 232 GHz

Aperture map (distance units)

ELEVATION

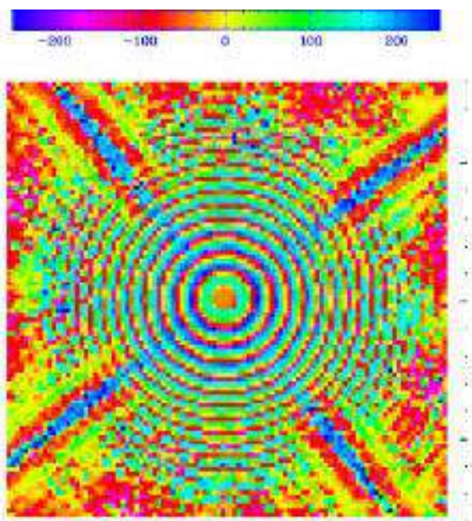


Amplitude

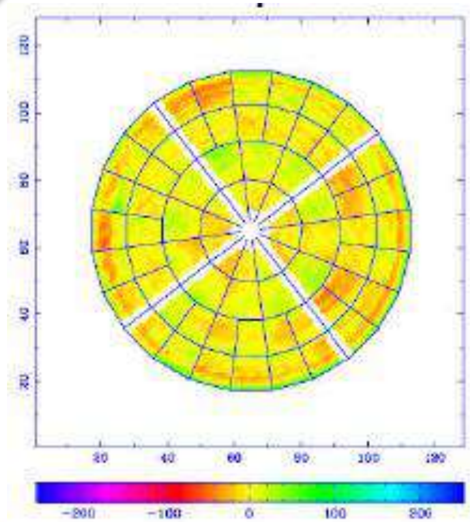


Fourier transform

ELEVATION



Phase

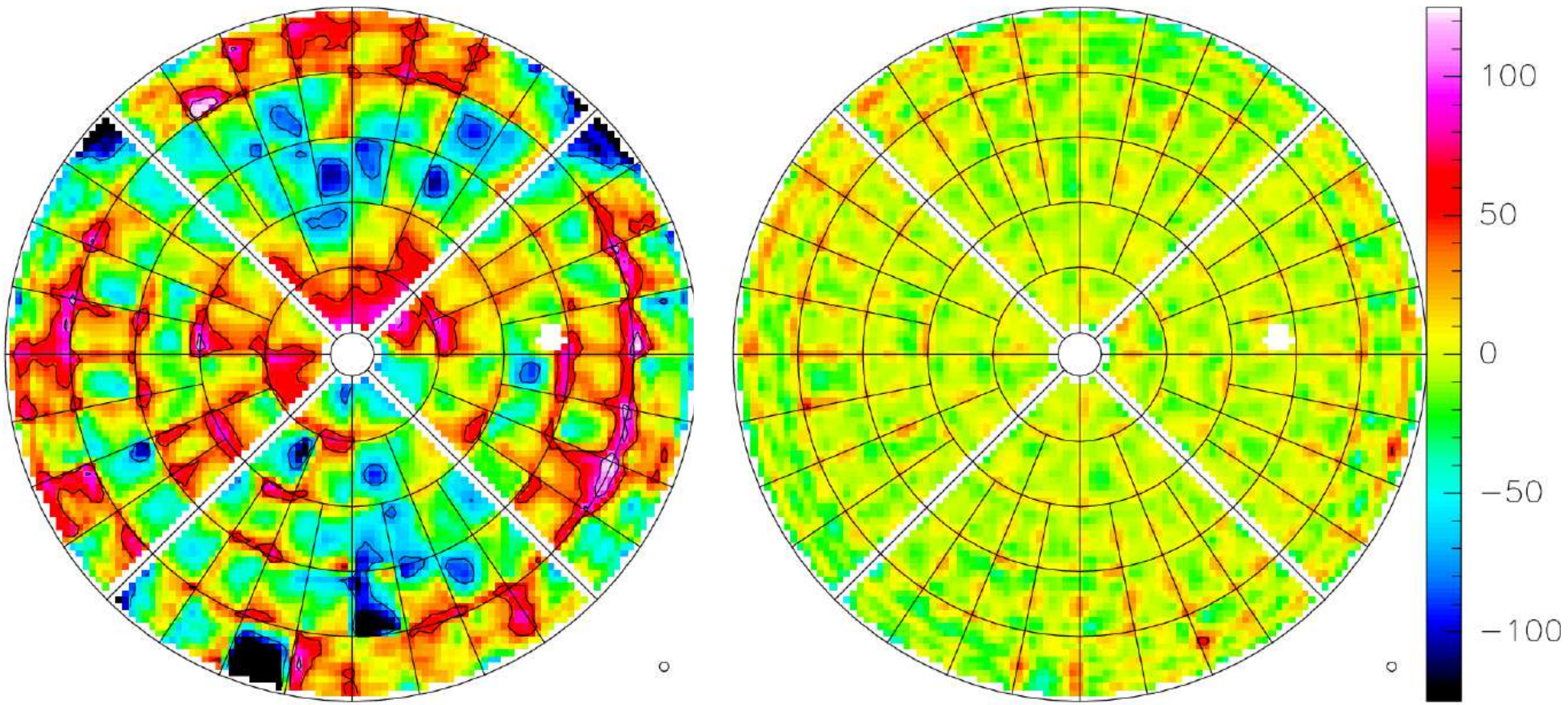


AZIMUTH

Holography: ALMA surface panel adjustment

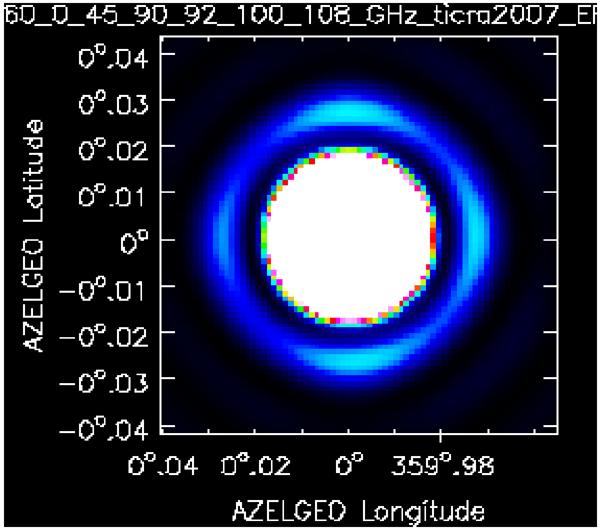
Phase map converted to path length error from ideal paraboloid

Before adjustment (43μm)   After adjustment (11μm)

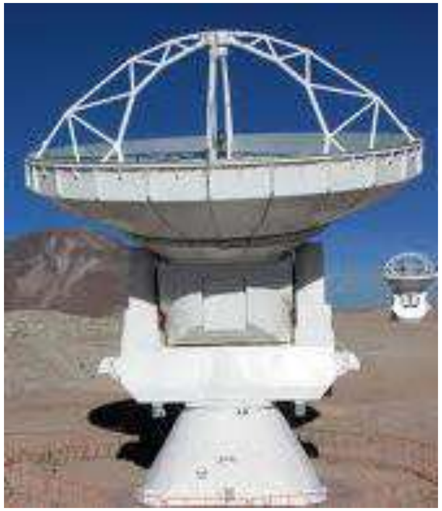


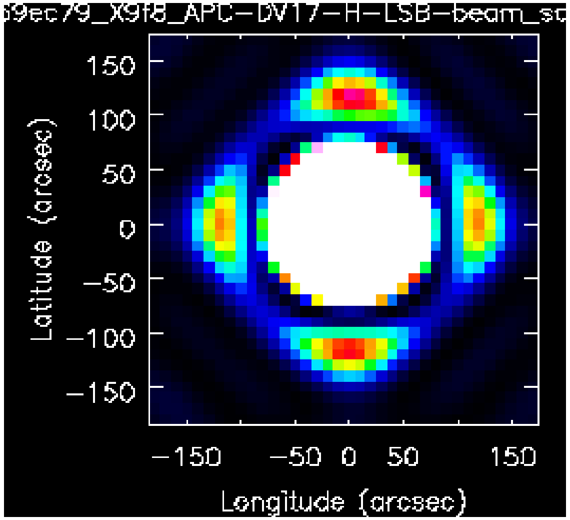
Holography: Effect of feed legs on beam

- Feedlegs block and scatter radiation prior to reaching the primary
- In some cases, they also block the path back up to the subreflector
- Sidelobe pattern rotates w.r.t. celestial objects: parallactic angle coverage needed for proper polarization calibration



AEC ALMA Antenna





Vertex NA ALMA Antenna

Front End polarization separation

For optimal sensitivity, we want dual-polarization receivers

Two types of devices can provide ~20dB purity with low loss:

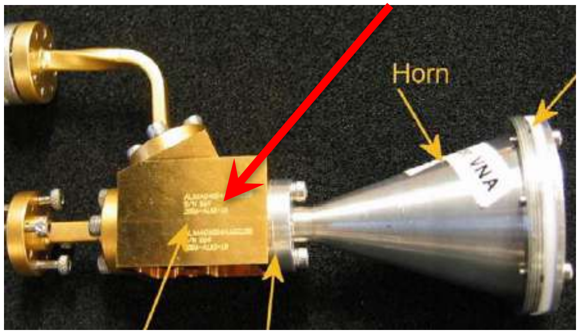
1) **Waveguide** (i.e. after the feed): Ortho-Mode Transducers (OMTs)

- Can be designed numerically (Maxwell's eqs.)
- Easy to machine when large (i.e. low frequency)

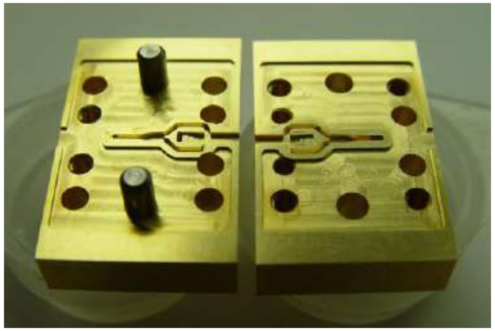
ALMA Band 3 OMT

Pol 0

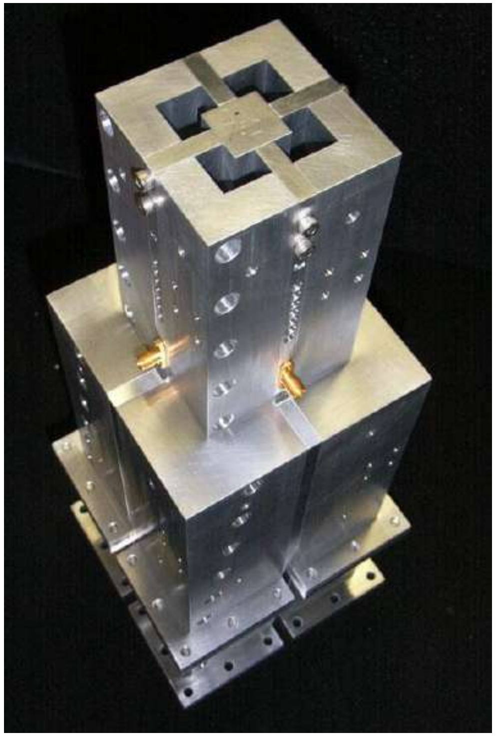
Pol 1



Band 6 OMT (opened)



VLA S-band (2-4 GHz)



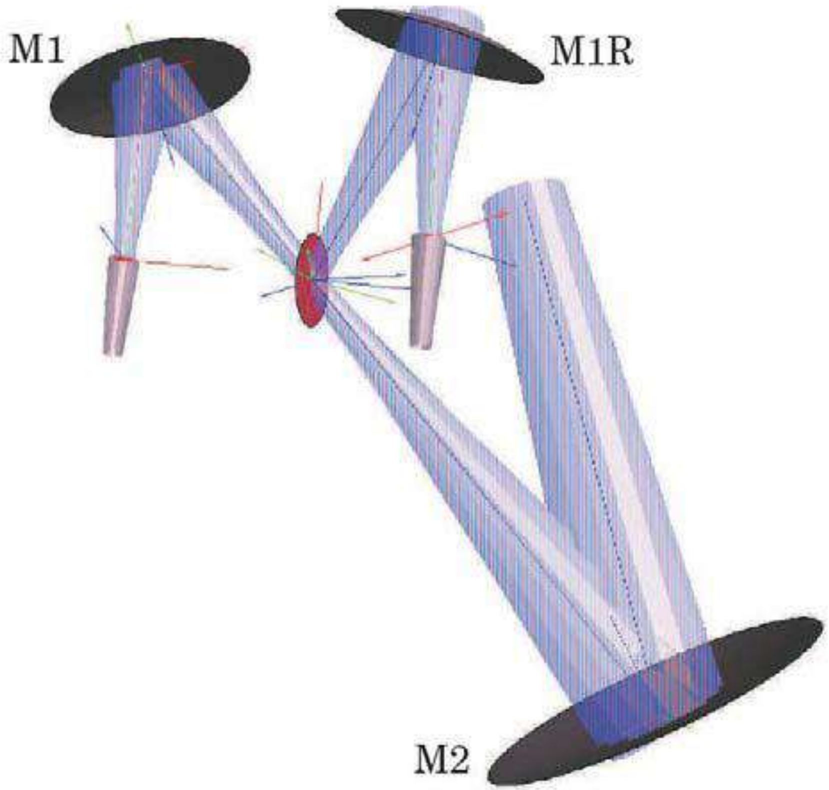
2) **Quasioptical** (i.e. in front of feed): Wire grid

- Advantage: easier to construct for high freq.
- Disadvantage: Alignment tricky ("squint" ~θ/10)

Polarization separation: ALMA Band 7 grid

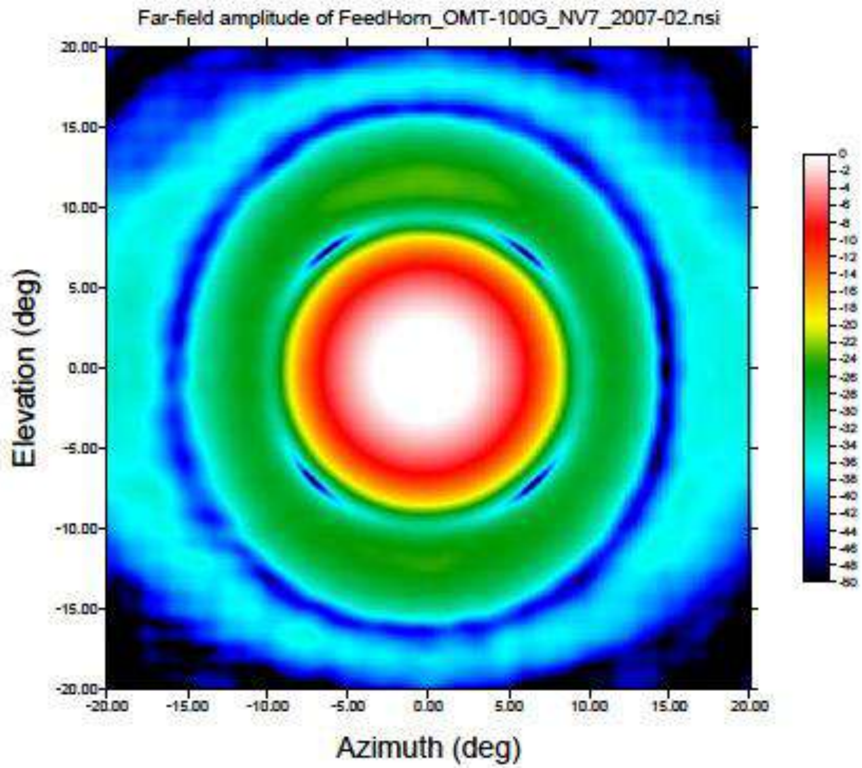
High frequencies: wire grid

- Reflects one linear polarization, passes the other
- Wire diameters of ~ 10 microns, fairly easy to wind
- Two feedhorns instead of one

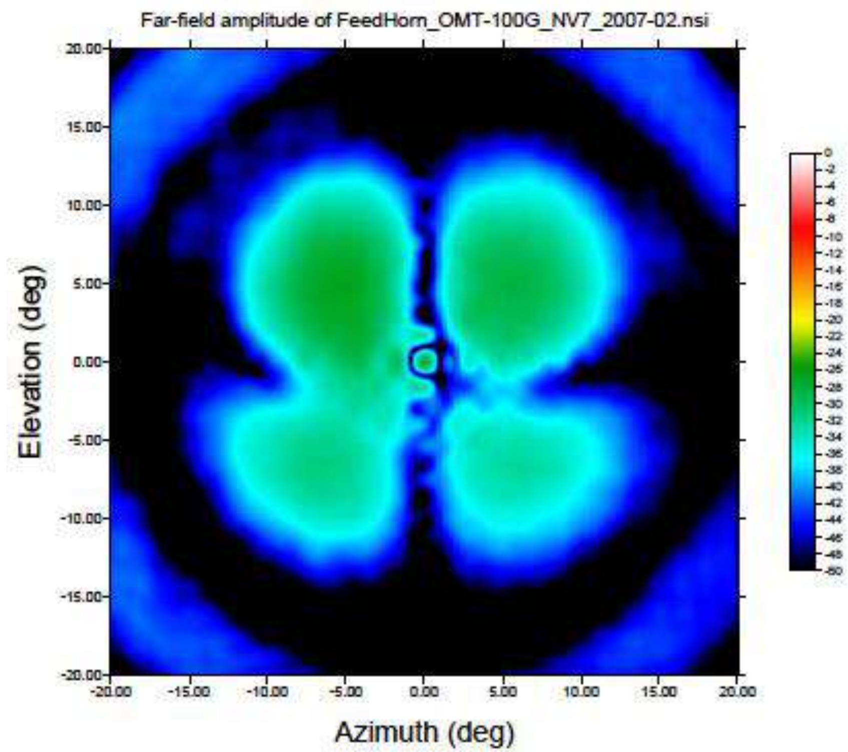


ALMA Cross-polarization patterns

Band 3 (100 GHz):
Co-polarization pattern



Off-axis cross-polarization pattern ("clover leaf")



Antenna thermal effects and metrology

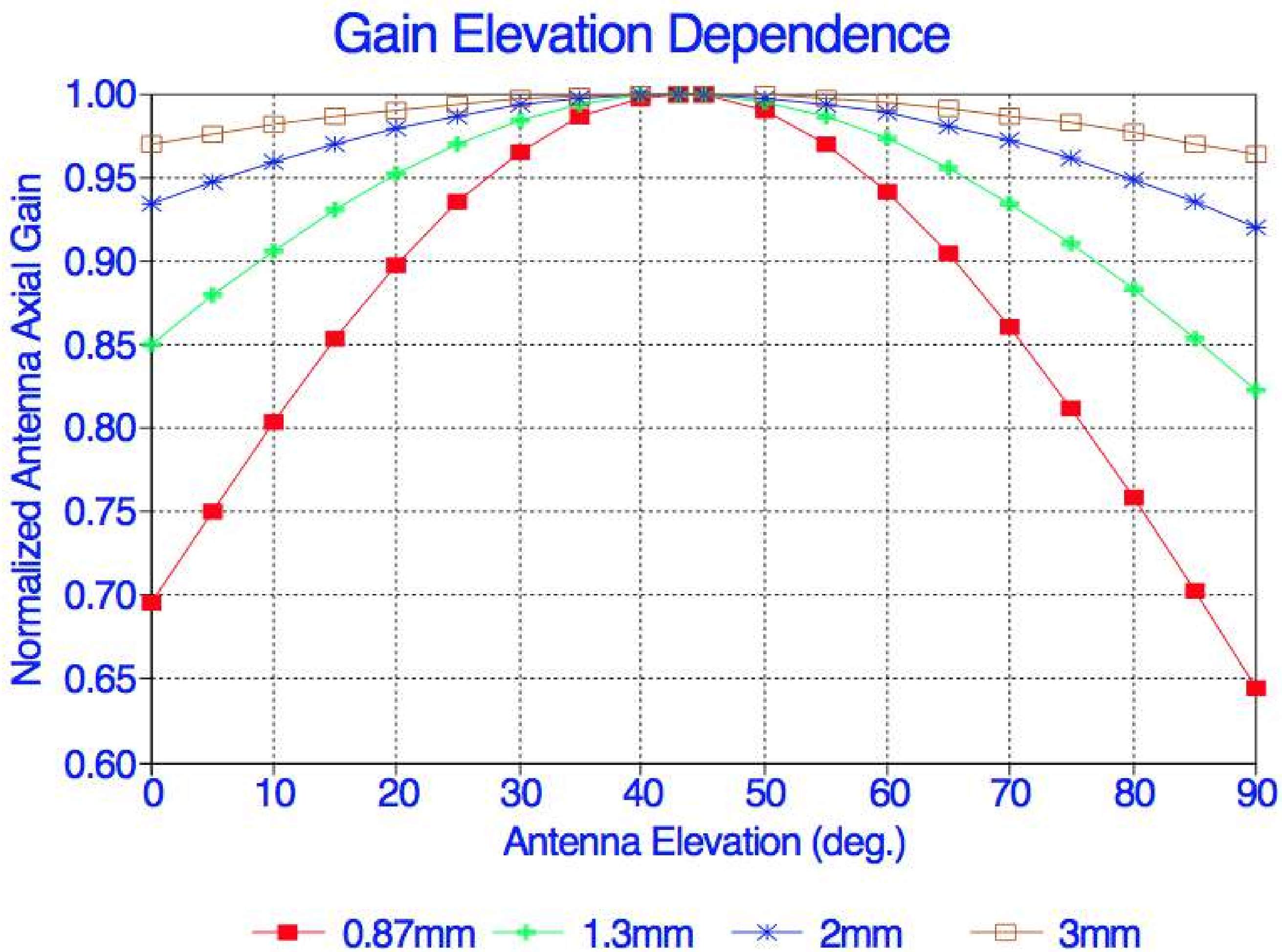
- Thermal gradient in antenna structure affect the focus, pointing and surface accuracy of antennas
- Performance is generally best during second half of the night when temperature has stabilized and dish has "relaxed"
- Some telescopes use "thermal terms" in their focus and/or pointing models using thermometers: e.g. IRAM 30m, GBT
- Metrology devices: inclinometers to measure tilts (e.g. GBT, ALMA)

ALMA	BUS	Number Rings/ Panels	Panel Material	Quad type[1]	Cabin	Drive System[2]	Metrology System[3]
Vertex	CFRP Al Invar	8/264	Al	+	Steel	Gear	4 linear displacement sensors + 1 two-axis tiltmeter (above the azimuth bearing)
Melco 12 m	CFRP	7/205	Al	+	Steel	Direct	Reference Frame metrology
Melco 7 m	Steel	5/88	Al	+	Steel	Direct	Thermal (main dish), Reference Frame metrology
AEM	CFRP Invar	5/120	Nickel Rhodium	x	CFRP	Direct	86 thermal sensors + 2 tiltmeters in yoke arms

Antenna gain curve

- Best efficiency is usually tuned to intermediate elevations
- Gravity distortions increase away from this point
- Similar curves for VLA are available in CASA

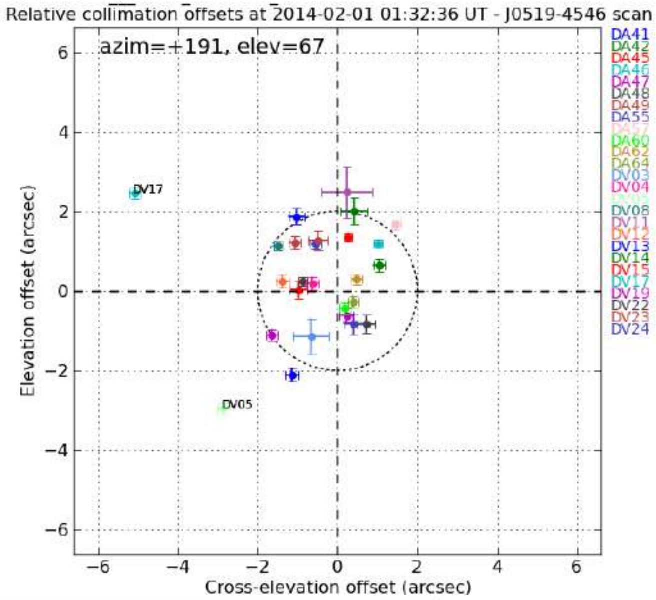
IRAM 30m (predicted, 1999)



Antenna pointing and tracking

Static errors: Blind pointing vs. offset pointing

- ALMA: blind=2", offset=0.6" rms (θ_{FWHM}/10 at Band 10)
- VLA: blind~15", offset=3" rms (θ_{FWHM}/17 at 50 GHz)

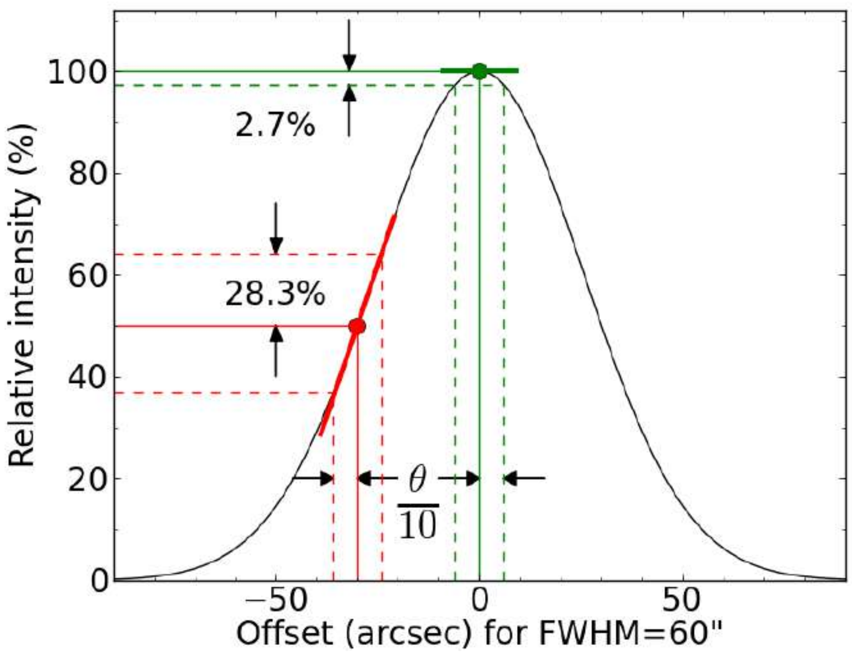


Dynamic errors: wind etc.

- VLA: tracking ~ 3" rms (no wind)

  i.e. peak excursions +-6"

  θ_{FWHM}/10 at 43 GHz



How good is θ_{FWHM} / 10 ?

not very good away from

the beam center!

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Mexico RTIUM

Antennas: How do they slew & track?

RA = 17:20:53.5
Dec = -35:47:00.0
LST = 15:43:12
Latitude = -23.0229
Longitude = -67.7549
Elevation = 5040m

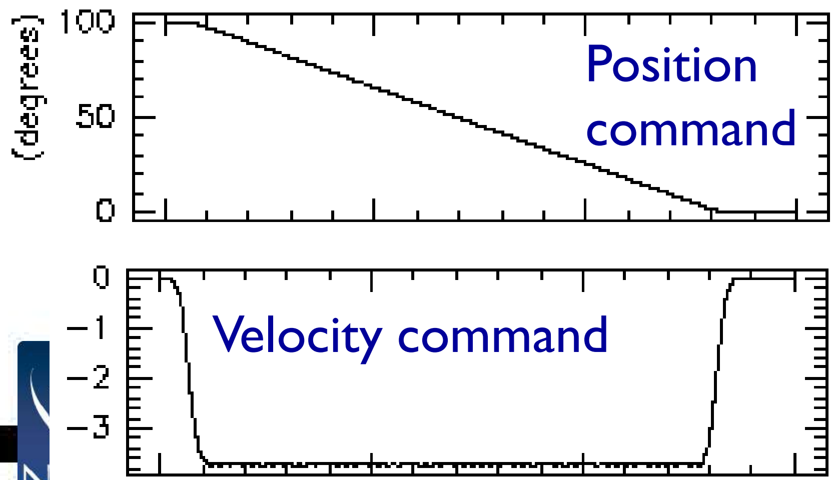
Azimuth angle & velocity
Elevation angle & velocity

?

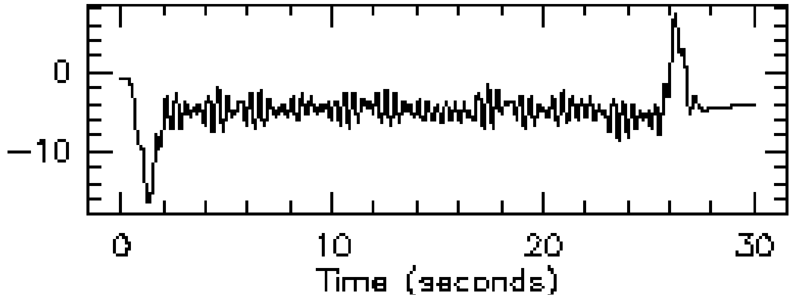
Servo system

Antenna Az/El servo loop overview

- **Input parameters**
  - Commanded position & tracking velocities (~5 Hz)
  - Pointing model: converts topocentric Az/El to actual Az/El
- **Multiple nested servo loops (software/firmware)**
  - **Position loop** (~5 Hz): **Encoder:** converts angular position of antenna axis to integer
    - **Velocity loop** (~100 Hz) **Tachometer:** converts motor shaft angular velocity to voltage
      - **Motor current (torque) loop** (~ a few kHz) **Resolver:** converts motor shaft angle to voltage or integer

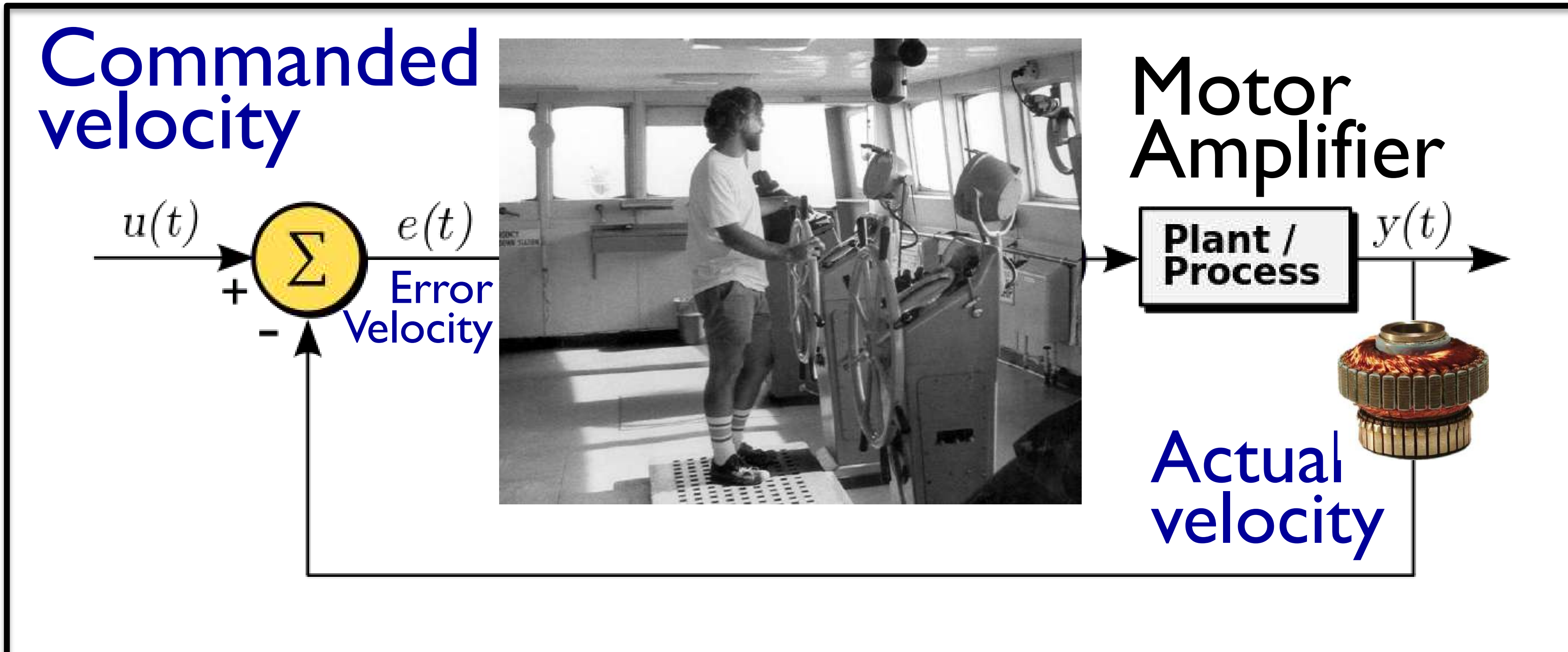


Motor Torque command



Detail of velocity servo loop: PID type

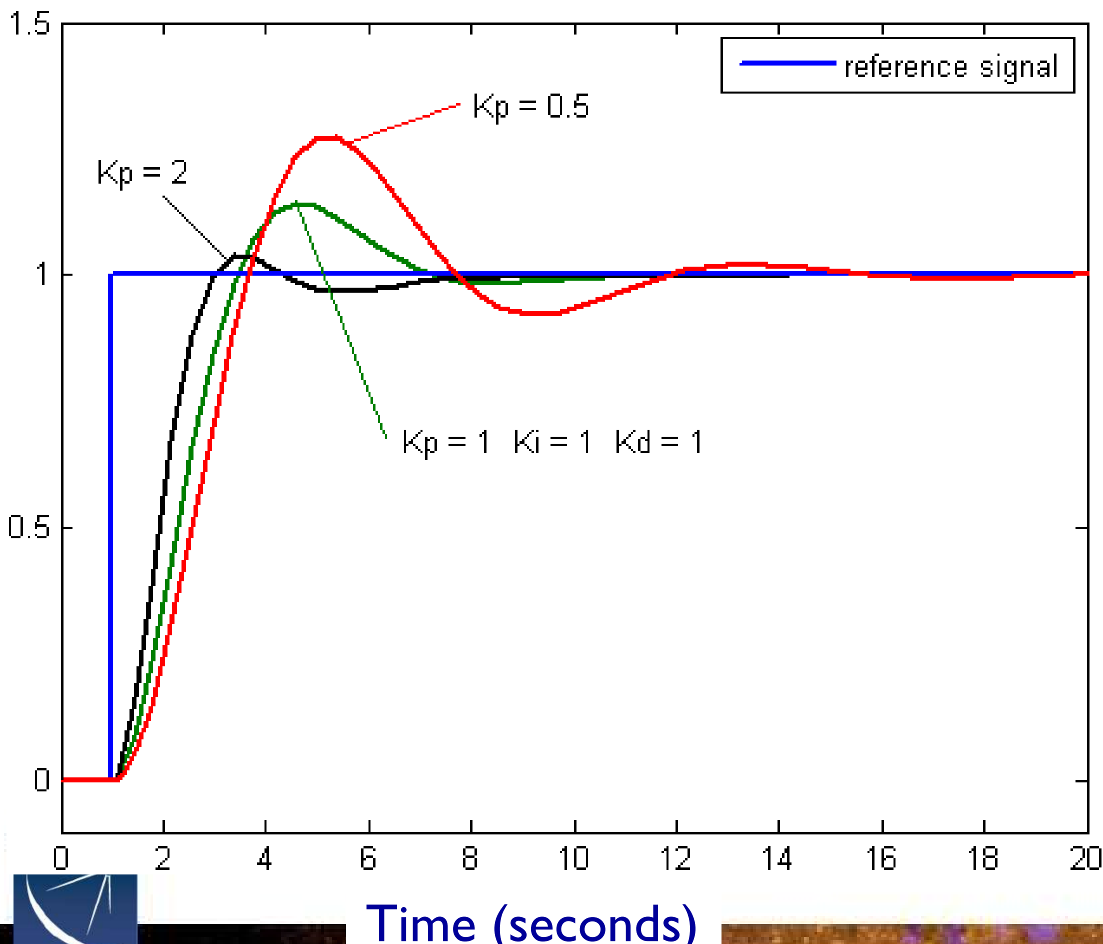
proportional / integral / derivative



The gains must be tuned for each loop: K_{pos}, K_{integ}, K_{deriv}

System response vs. gain

Trade-off between reducing overshoot and reducing oscillation frequency to below the antenna's lowest resonant frequency



- Servo systems use many hardware and software safety checks to avoid runaway conditions or damage.
- VLA is currently revitalizing it servo system with modern components

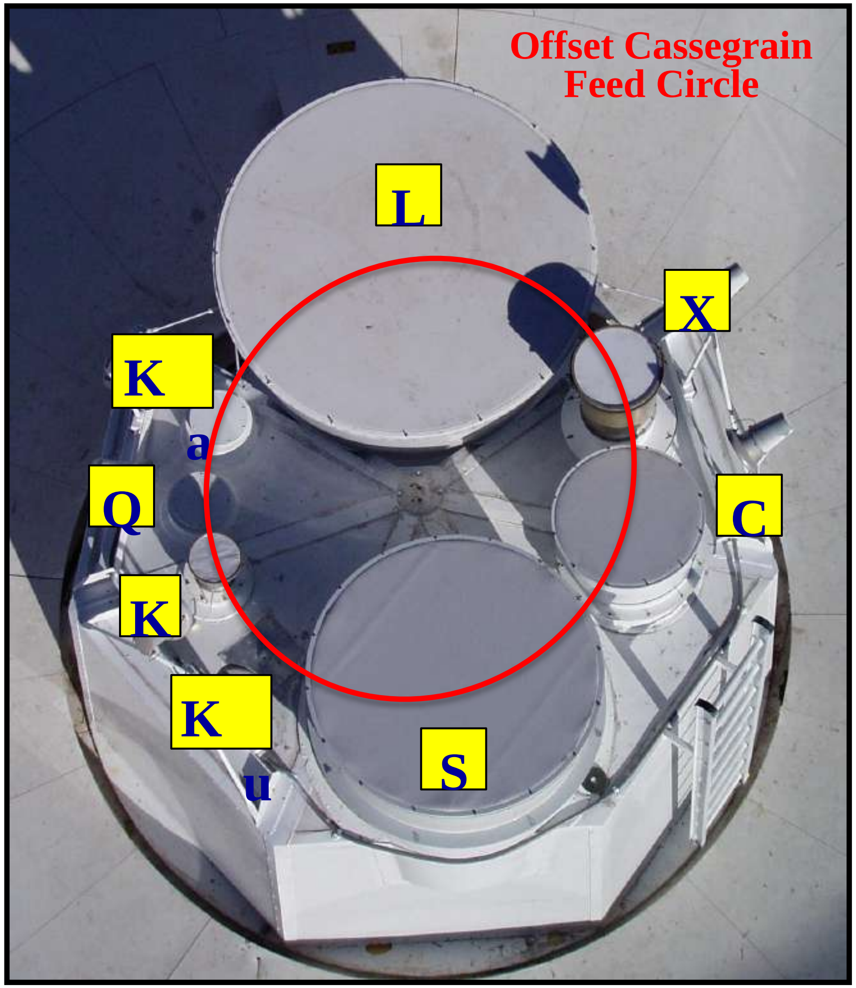
Role of an receiver

Linearly amplify weak RF signals while adding minimal noise, and downconvert them to room-temperature output signals at a few GHz (called "IFs") on coax cables suitable for digitization

- Receivers are often called "Front Ends" or FE

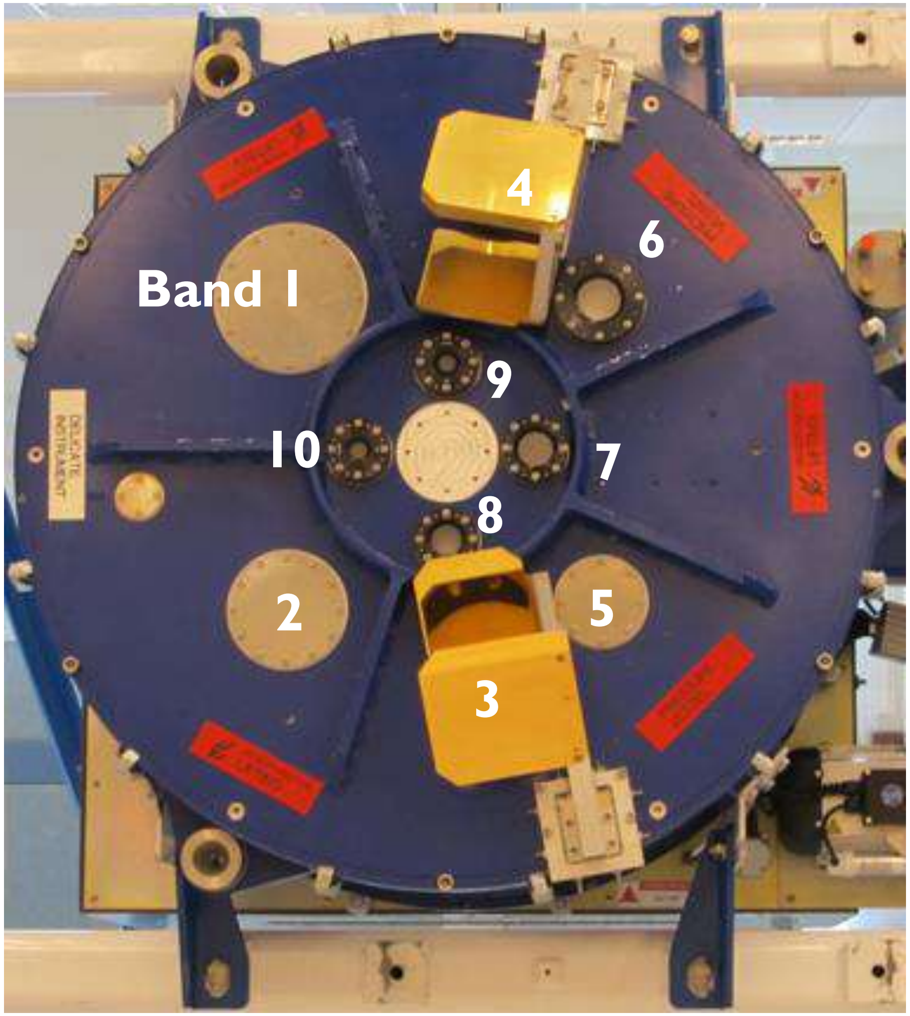
VLA receiver summary

Wavelength Band (letter code)	Nominal frequency range (GHz)	Polarization, operating temperature
4 m (4)	.058-.084	Linear, 300K
90 cm (P)	0.23-0.47	Linear, 300K
20 cm (L)	1.0-2.0	Circular, 15K
13 cm (S)	2.0-4.0	Circular, 15K
6 cm (C)	4.0-8.0	Circular, 15K
3 cm (X)	8.0-12.0	Circular, 15K
2 cm (Ku)	12.0-18.0	Circular, 15K
1.3 cm (K)	18.0-26.5	Circular, 15K
1 cm (Ka)	26.5-40.0	Circular, 15K
0.7 cm (Q)	40.0-50.0	Circular, 15K



ALMA receiver summary (dual linear pol.)

Band (number code)	Frequency range (GHz)	Sidebands, Polarization splitter
7 mm (1)	32-50*	SSB, OMT*
4 mm (2)	67-90*	?SB, OMT*
3 mm (3)	84-116	2SB, OMT
2 mm (4)	125-163	2SB, OMT
1.6 mm (5)	163-211	2SB, OMT
1.3 mm (6)	211-275	2SB, OMT
0.9 mm (7)	275-373	2SB, Wire grid
0.7 mm (8)	373-500	2SB, OMT
0.45 mm (9)	600-720	DSB, Wire grid
0.35mm (10)	787-950	DSB, Wire grid

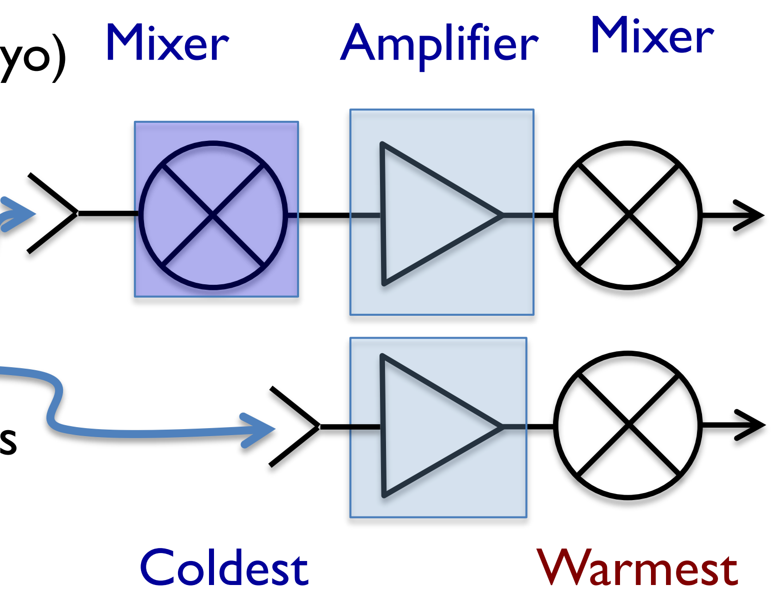


* under development

Overview of Receivers and IF systems

Three basic technological limitations dictate what we do:

1. We can build good amplifiers up to ~100 GHz
2. We can digitize signals of bandwidth up to ~2 GHz
   - ➔ to observe at >100 GHz, the front-end must be a **mixer**
   - ➔ to observe a bandwidth >2 GHz, you need a **mixer in the IF chain**
3. Mixers and amplifiers must be cold when used as the front-end
   - – Cold amplifiers need ~15K (2-stage cryo)
   - – SIS mixers need 4K (3-stage cryo)



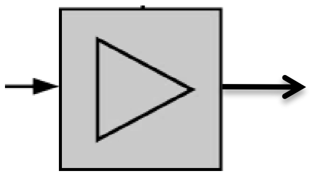
So:

- – ALMA FE needs cold mixers & amplifiers
- – JVLA FE needs cold amplifiers
- – Both also require room temperature mixers & amplifiers (prior to digitization)
- – **Mixers are key devices!**

Amplifiers and mixers

Let's compare an amplifier and a mixer:

1. Amplifiers are <u>2-port</u> devices: one input and one output

IN  OUT (10-30dB stronger, same frequency)

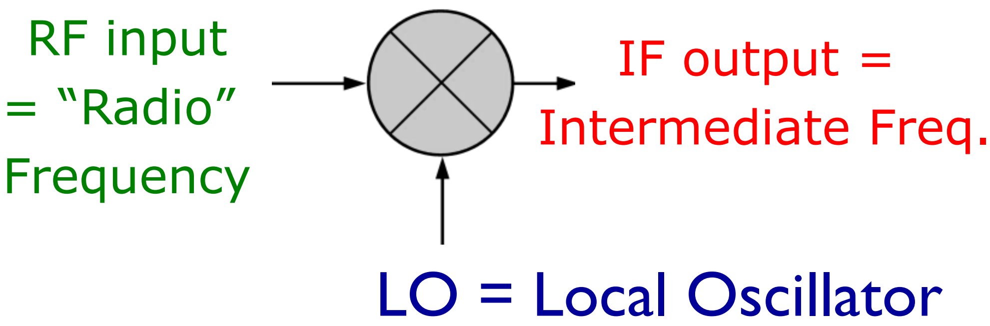
Example: NRAO Cryogenic Low Noise Amplifiers (LNAs) using Heterostructure Field Effect Transistors (HFETs) used on the VLA, VLBA, GBT:

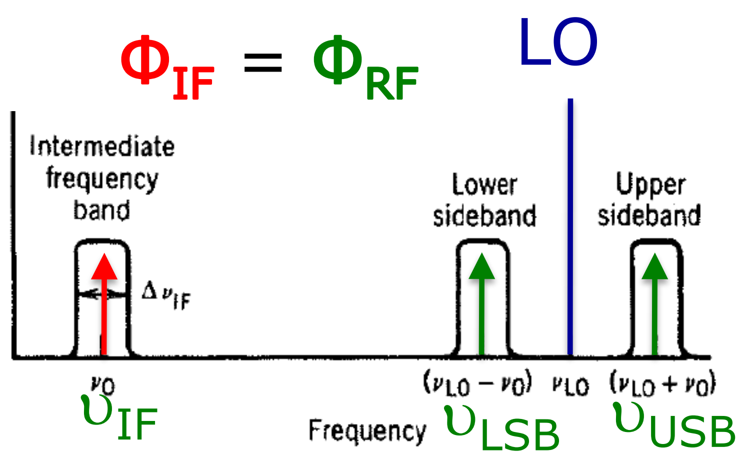
- Operate at ~15 K
- Tnoise ~ 5 hf/k
  (i.e. 5 x quantum limit)
- M. Pospieszalski (2012)
  (MIKON conference)

What is a mixer?

Mixers are <u>3-port</u> devices: LO and RF inputs, and IF output.

- Invented around WWI for radio direction finding (see IEEE Microwave Magazine Sept. 2013 special issue).
- They multiply the LO & RF signals and <u>transfer the phase from the RF to the IF</u> by "heterodyning". Typically the IF contains signals from two sidebands.
- They are key components for interferometers!!





$$\sin(2\pi f_1 t)\sin(2\pi f_2 t) = \frac{1}{2}\cos[2\pi(f_1 - f_2)t] - \frac{1}{2}\cos[2\pi(f_1 + f_2)t]$$

Different Kinds of Mixers

Inexpensive Off-the-Shelf room temperature mixers:

- Used in IF circuitry after the received signal has been sufficiently amplified

Delicate, cryogenic SIS junctions mixers used as FE

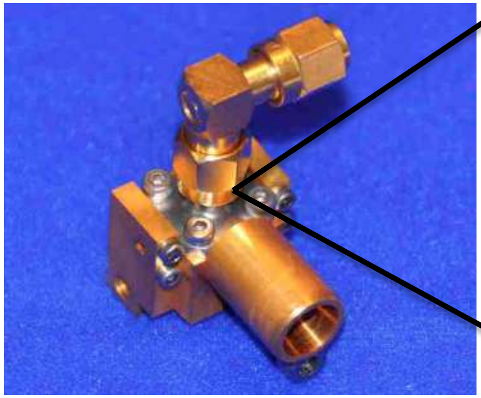
SIS = Superconductor – Insulator – Superconductor

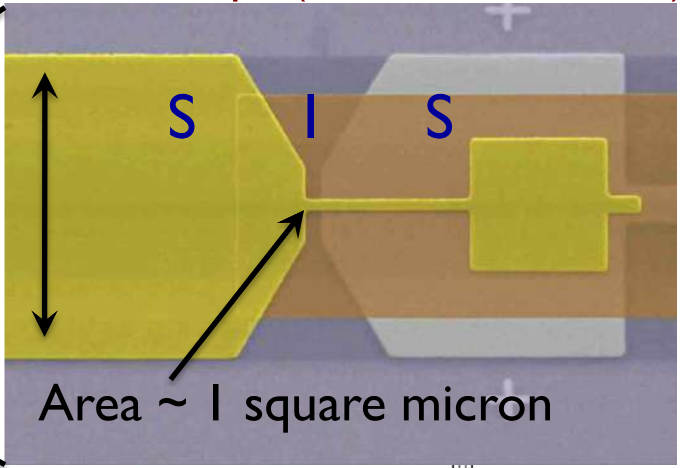
First astronomical use: Dolan, Phillips & Woody (1979)

Theory: Tucker (1979)

Image of SIS junction from Electron Microscope (Hedden et al. 2010)

SMA 650 GHz mixer block (Nb/AlOx) with feedhorn (for LO and RF input)

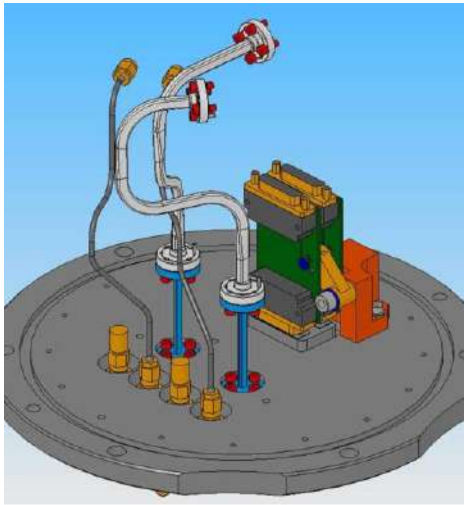




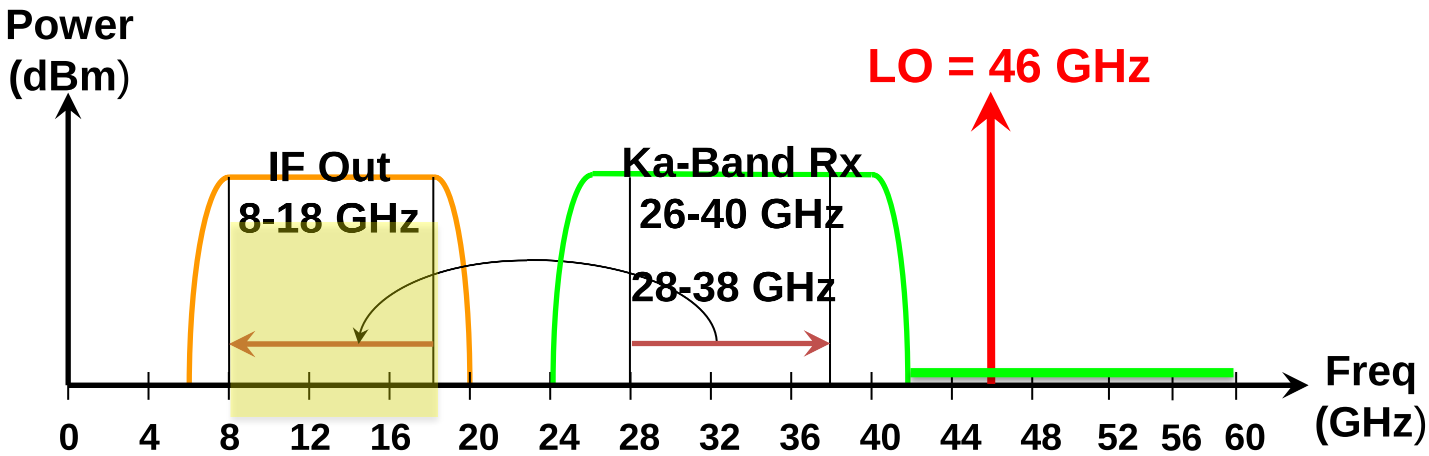
Sidebands

Receiver design options: SSB, 2SB, 1SB, DSB

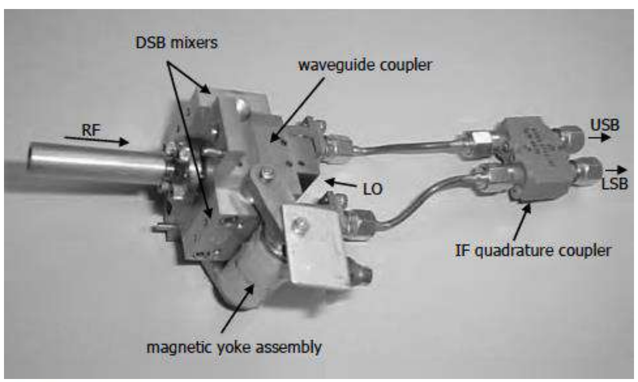
- **SSB:** the RF signal is filtered so that only one SB emerges from the mixer
  - Examples: VLA receivers
- **2SB:** the mixer separates the two SBs with a 90° hybrid quadrature coupler. Rejects signal and atmospheric noise of the image SB by 10-20 dB
  - Examples: ALMA Bands 3 – 8,
- **1SB:** a 2SB system where one SB output is simply terminated (i.e. unused)
  - Examples: ALMA Band 2 NA prototype
- **DSB:** both sidebands are superposed on one another
  - Examples: ALMA Bands 9-10, SMA
  - Requires 90 deg Walsh modulation on the LO to separate them (but only for inteferometry)



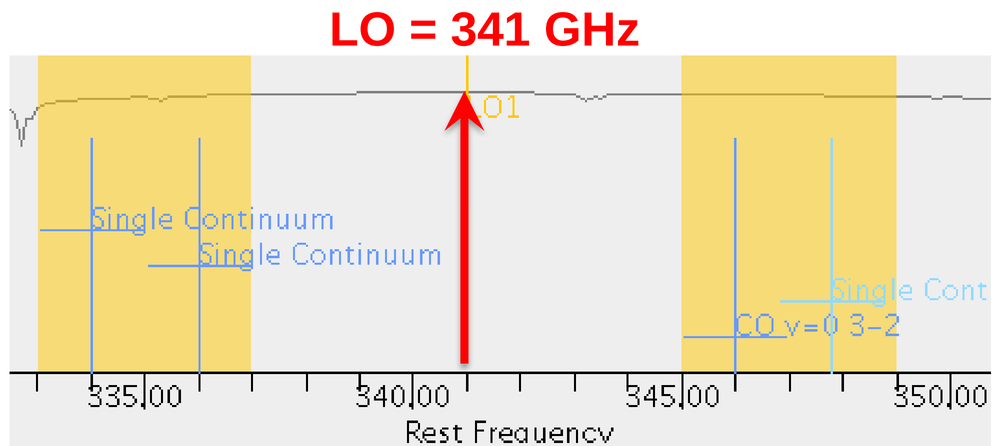
SSB: VLA receivers

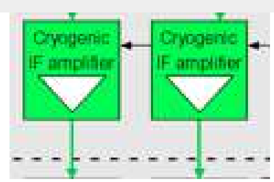


2SB: ALMA
Bands 3-8

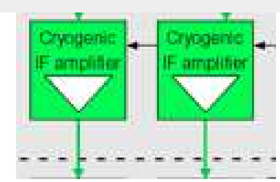


Band 7: Meier et al 2005





LSB
2 pols



USB
2 pols

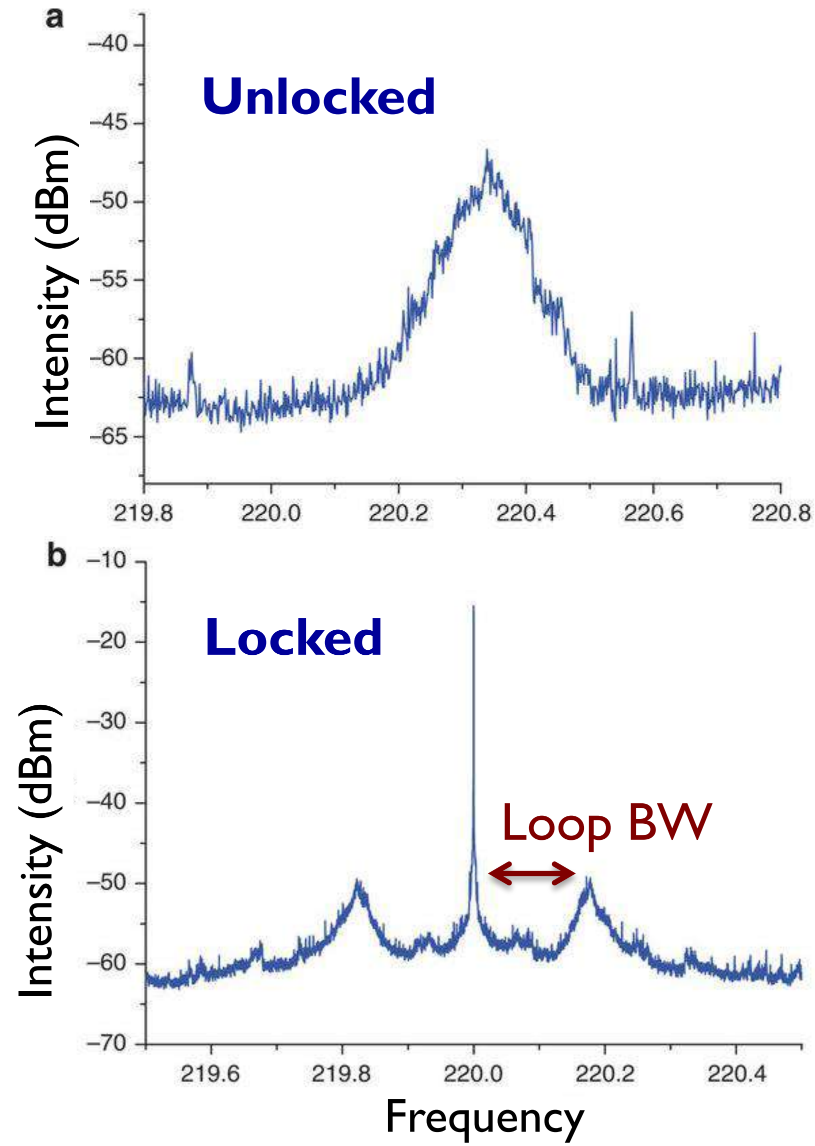
Local oscillators

Goal: Deliver stable, accurate phase reference to a remote mixer

Problem: Signals lose S/N upon transmission, and must be "cleaned up"

- Phase lock loop (PLL) circuit is analogous to an antenna drive servo
- Compares phase of two signals, correcting at BW ~ 1 MHz

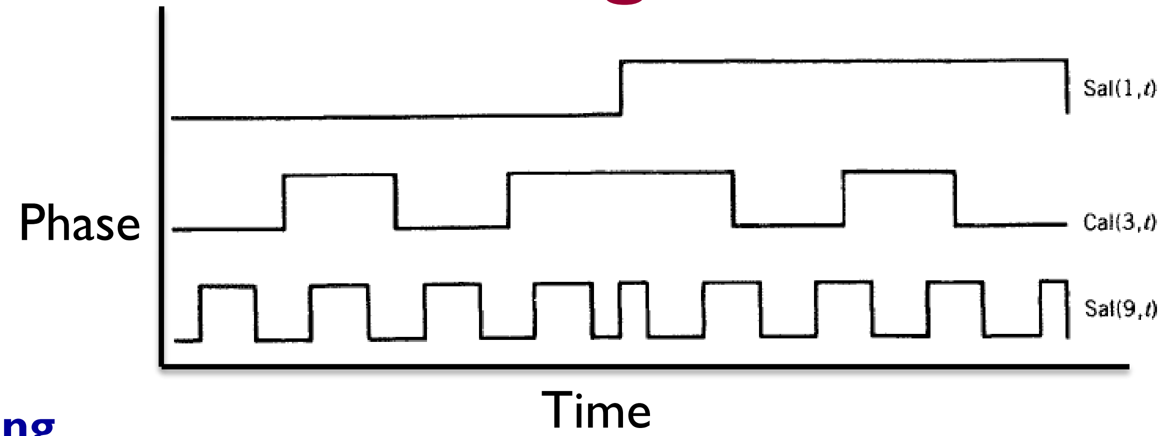
ALMA YIG oscillator



LO Modulation: Walsh switching

See Thompson, Moran & Swenson (chapter 7); ALMA Memo 586

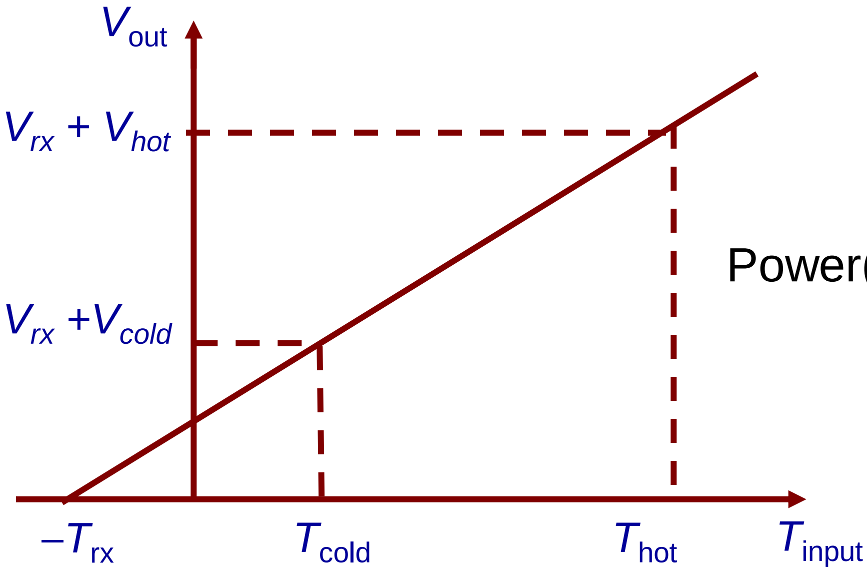
- **Impose on LO**
- **Remove in correlator**
- **180 degree Walsh switching**
  - Suppresses spurious signals (birdies) that arise between the frontend and the digitizer
- **90 degree Walsh switching**
  - Allows you to separate sidebands in cross-correlation
  - Will double the bandwidth for DSB receivers (Bands 9-10)
- **LO Offsetting (see ALMA Memo 287)**
  - Suppresses the opposite sideband (by moving its fringe to several kHz and letting it "wash" out)
  - Suppresses spurious signals, but does not reduce broadband noise



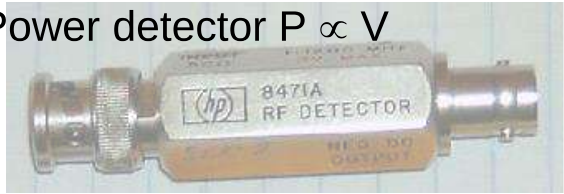
Sensitivity: T_{rx} and the Temperature Scale

Good receiver systems have a linear response: $P_{out}\ \mu\ V_{out} = G*(T_{input} + T_{rx})$

Unknown slope (G) **Calibrated 'load'** (T_{input}) **Receiver temperature** (T_{rx})



Power detector P ∝ V

Power(ν) ⇨  ⇨ Voltage

To measure T_{rx}, you need measurements of two calibrated 'loads'. In the lab, you use:

T_{cold} = 77 K liquid nitrogen load

T_{hot} = Room temperature load

Starting from $y = mx + b$

$$T_{RX} = \frac{T_{HOT} - YT_{COLD}}{Y - 1}$$

Define the "Y" factor

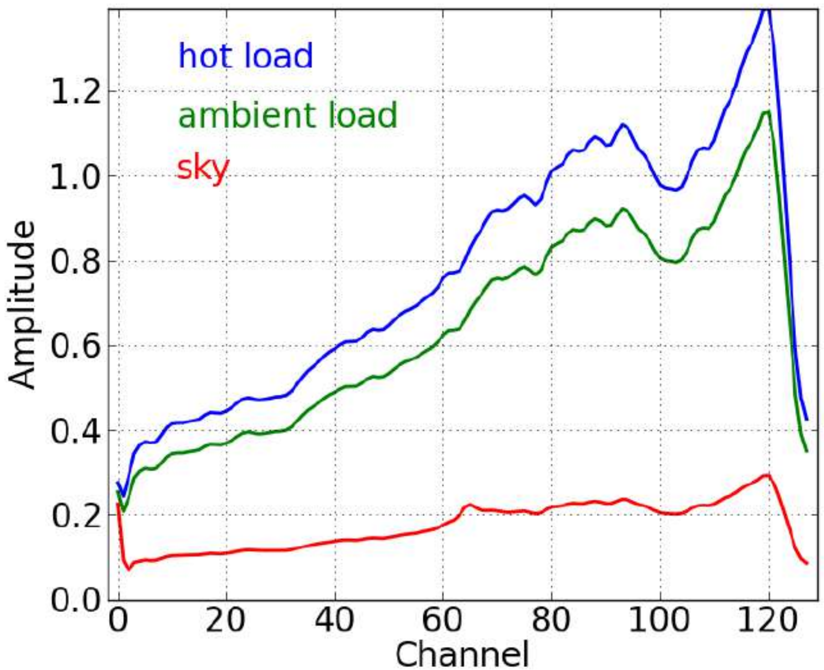
$$Y = \frac{V_{RX} + V_{HOT}}{V_{RX} + V_{COLD}}$$

$$G[Volt/Kelvins] = \frac{[V_{RX} + V_{HOT}] - [V_{RX} + V_{COLD}]}{T_{HOT} - T_{COLD}}$$

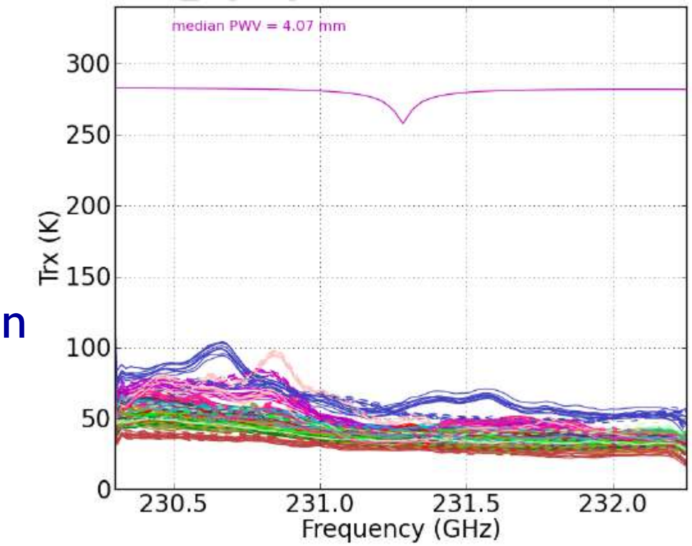
NRAO New Mexico Consortium

ALMA Sensitivity: Band 6 (230 GHz)

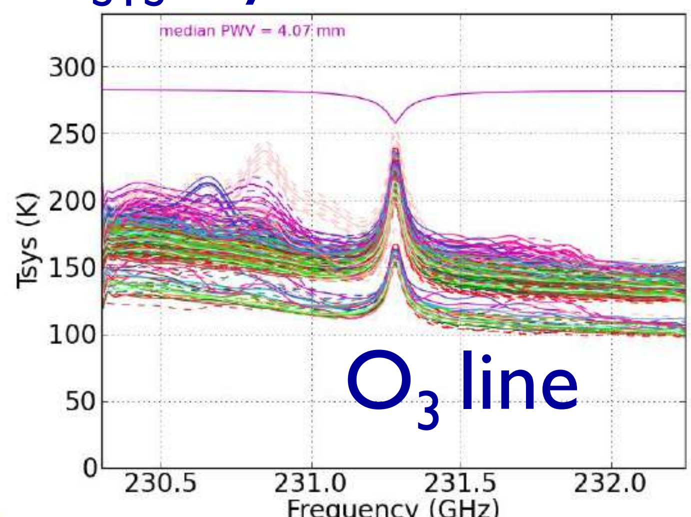
- Autocorrelation spectra from Tsys scan
- Note 3dB IF power variation vs. freq
- Shape is removed from cross-correlation



T_{RX}: receiver sensitivity

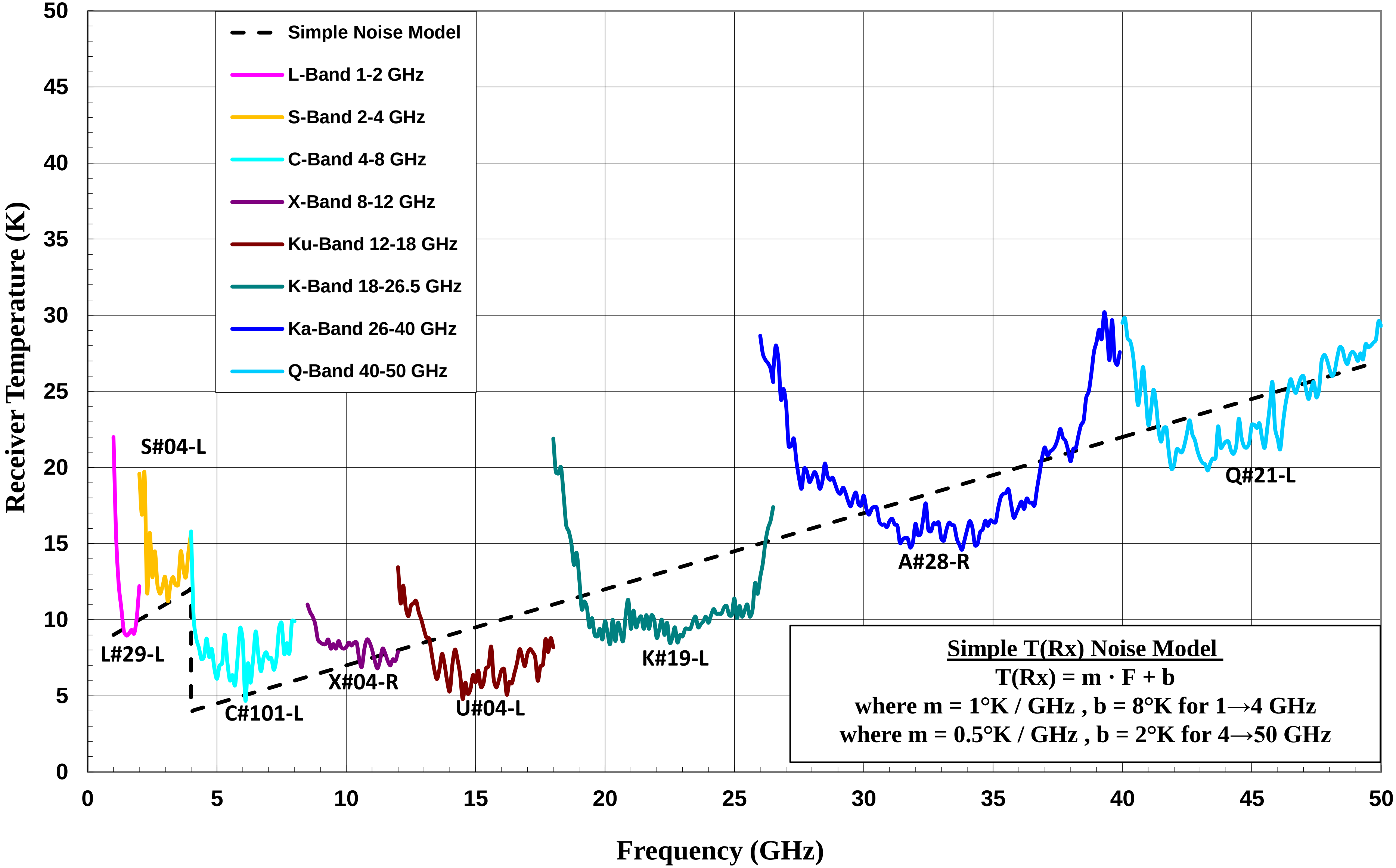


T_{SYS}: system sensitivity



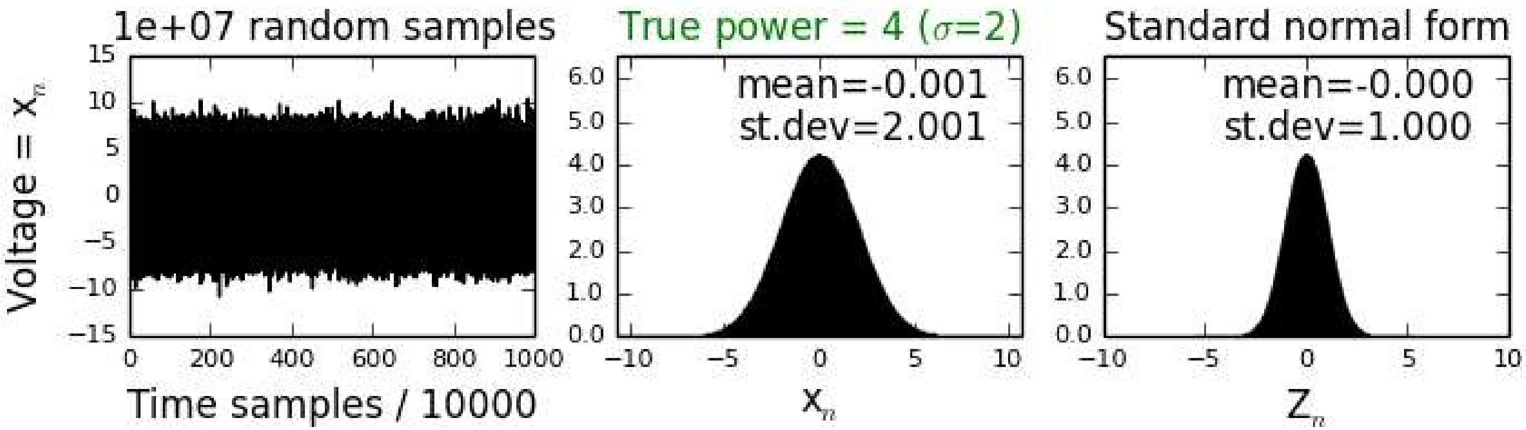
T(Rx) vs. Frequency for JVLA Receiver Bands

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



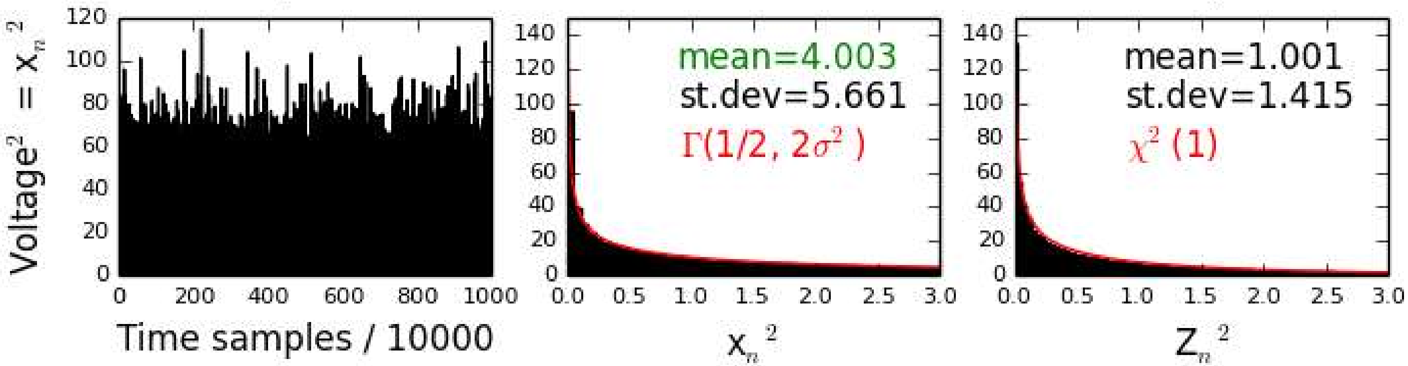
Radiometer equation derivation & simulation

1. Consider a sample time series of an RF signal: $x_n \sim N$ (mean=0, variance=σ^2)
2. Normalize it by its standard deviation: $Z_n = x_n / \sigma$, $x_n = \sigma Z_n$



3. Square this to get the power: $Z_n^{\ 2} = \chi^2(1)$ is the Chi square distribution with 1 d.o.f.
4. $x_n^{\ 2} = \sigma^2 Z_n^{\ 2} = \Gamma(1/2\ , 2\sigma^2)$ = the gamma distribution (c.f. constant * Chi square)

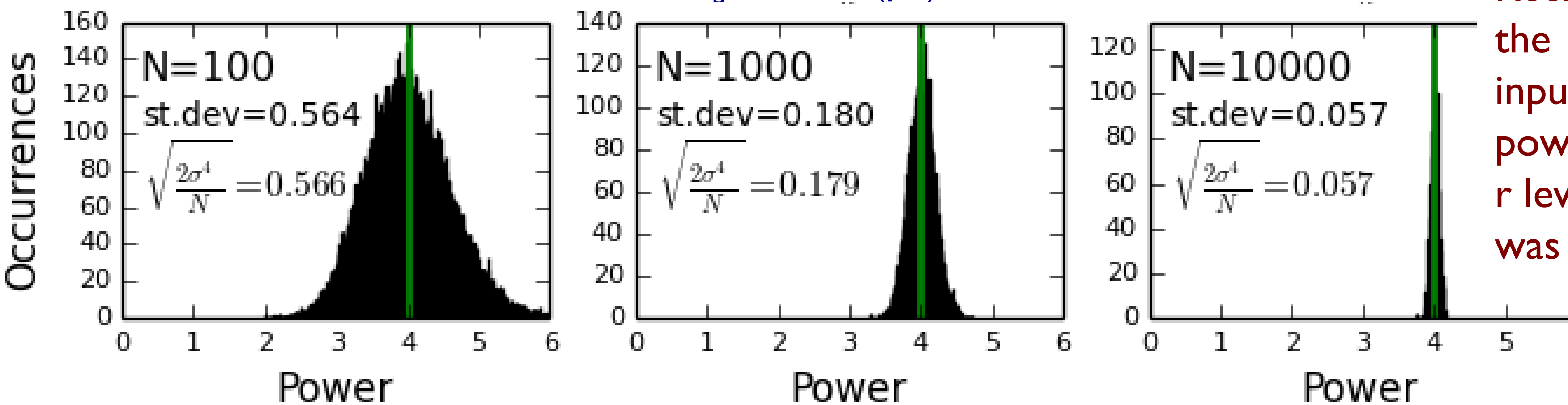
   with expectation mean = $\mu_{gamma} = \sigma^2$, and expectation variance $=\sigma^2_{gamma} = 2\sigma^4$



Radiometer equation derivation

5. The Nyquist sample rate is twice the bandwidth (2β) and the time interval of the data is τ, making the number of statistically independent samples $N = 2\beta\tau$

6. The Standard Error of the Mean* states that the sample power as computed from $(1/N)\,\Sigma x_n^2$ will have a distribution variance of $\sigma^2_p = 2\sigma^4/N = 2\sigma^4/(2\beta\tau) = \sigma^4/(\beta\tau)$ and thus its standard deviation is $\sigma_p = \sigma^2 / \sqrt{(\beta\tau)}$



Recall the input powe r level was 4!

7. Substitute μ_{gamma} (from Step 4) for σ^2 in the numerator: $\sigma_p = \mu_{gamma} / \sqrt{(\beta\tau)}$

   NOTE: μ_{gamma} is the expectation mean of x_n^2 and is equivalent to the sample mean power P for large N. This gives: $\sigma_p = P / \sqrt{(\beta\tau)}$

8. Radiometer output power in RJ limit is: $P = k T \beta G$ (where G = gain)

   Thus, $\sigma_p / P = \sigma_T / T$ and $\boxed{\sigma_T = T / \sqrt{(\beta\tau)}}$ independent of Gain!

(*e.g. Casella & Berger 2002)

Conclusions and Further reading

- Knowing a bit about the signal path can really help you understand your data, especially when there are problems or caveats (such as just how good is that primary beam correction?)

- For more information on ALMA antennas, receivers, and correlators, see the ALMA Technical Handbook at http://almascience.org
- Also, see my ADS Private Library on ALMA technology:
  http://adsabs.harvard.edu/cgi-bin/nph-abs_connect?library&libname=ALMA+technology&libid=464295c89a
- And my ADS Private Library on holography:
  libname=Holography&libid=464295c89a
- For more info on EVLA receivers:
  http://www.aoc.nrao.edu/~pharden/fe/fe.htm

Extra Slides

Safety is #1 priority

Hardware

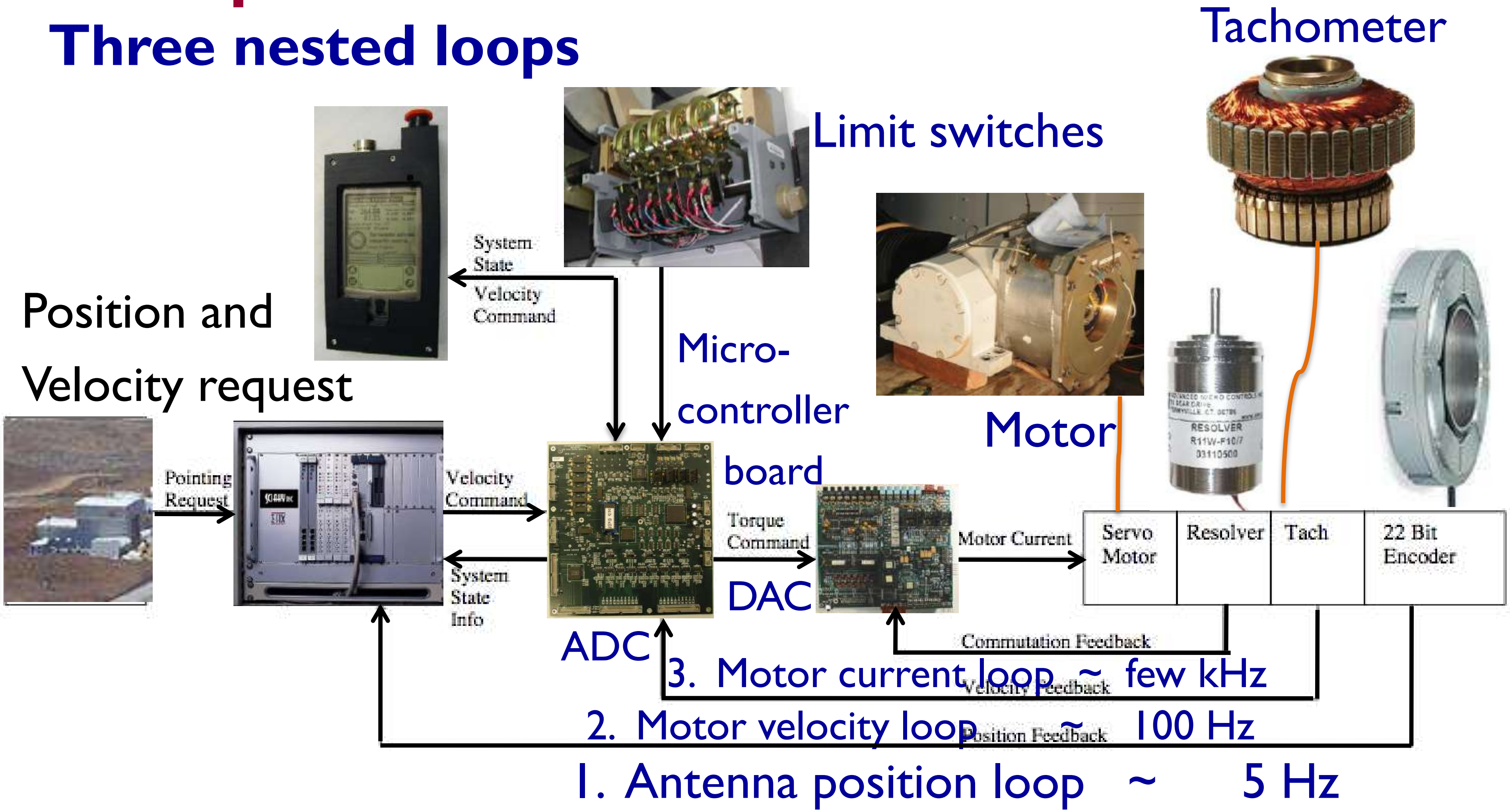
- Limit switches, 2 per direction per axis
- Hardstops must decelerate antenna from Vmax without destroying antenna
- Loss of power should cause brakes to engage (i.e. power holds them open)
- Applying brakes at full speed should not destroy antenna
- Manual E-stop switches prominent, with no Silicon in the circuit
- Watchdog timer: if microcontroller fails to clear it every few ms, engage E-stop
- Philosophy: if any wire breaks, system should stop as gracefully as possible

Software:

- Software limit switches
- Microcontroller must deactivate motors & apply brakes if:
  - encoder stops sending data, or antenna computer stops sending new values
  - tachometer reports overspeed, or differs from encoder derivative
  - Any large oscillation is detected

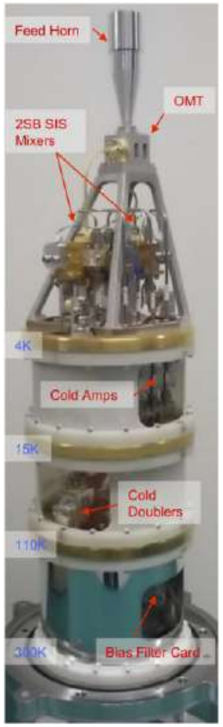
Example: SMA antenna servo

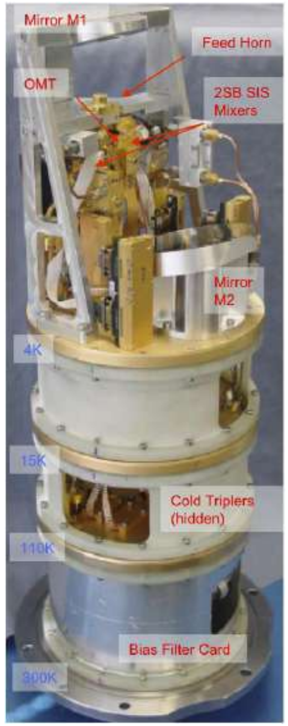
Three nested loops

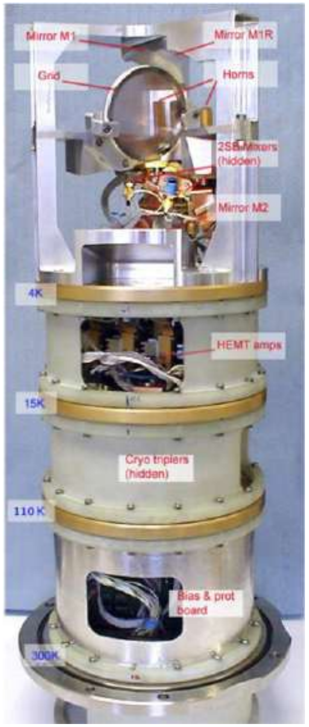


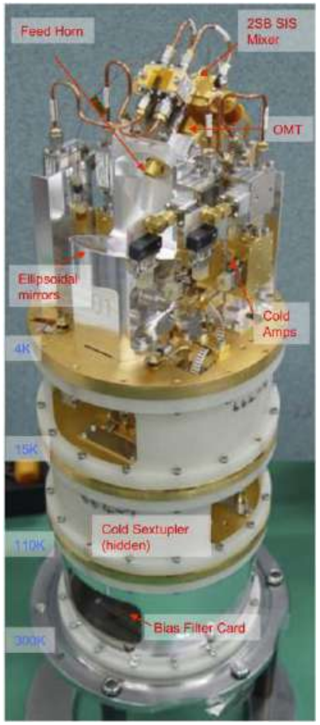
ALMA Receivers (dual linear polarization)

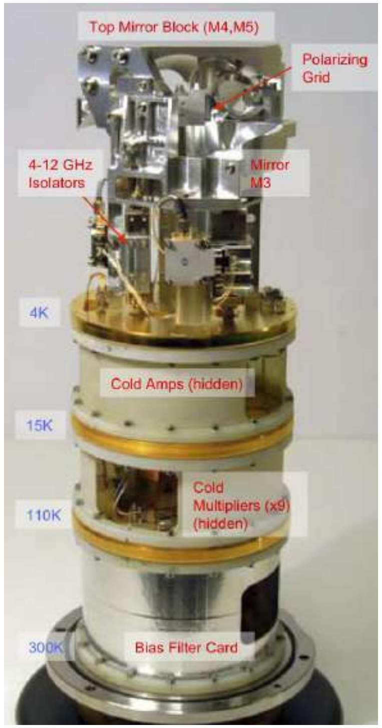
Lens, OMT	OMT	OMT	Wire grid	OMT	Wire grid
Band 3	Band 4	Band 6	Band 7	Band 8	Band 9
84-116	125-163	211-275	275-373	385-500	600-720 GHz



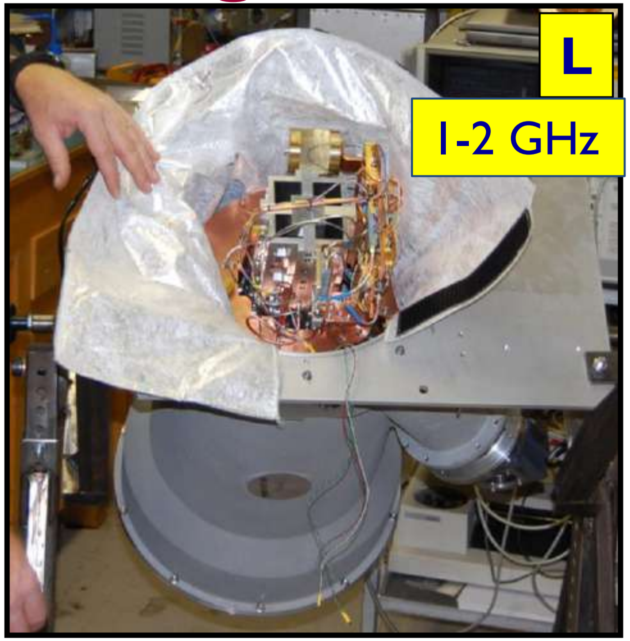


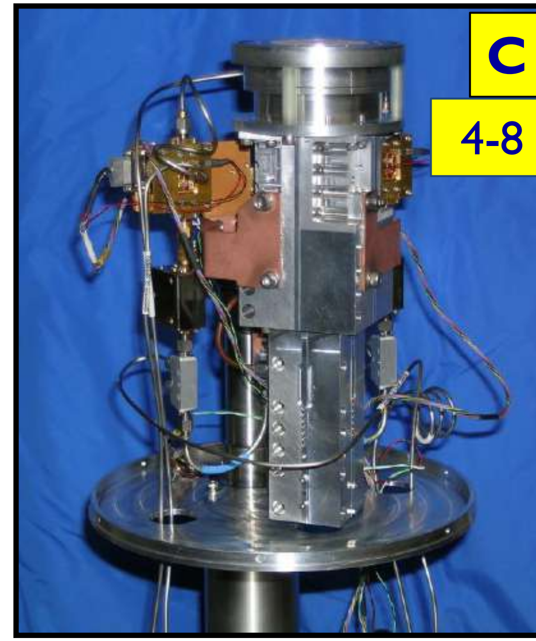


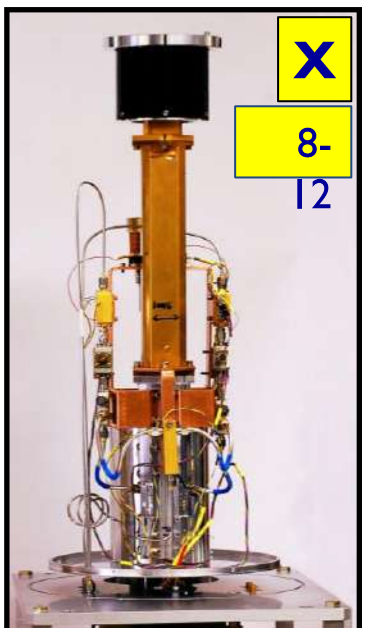


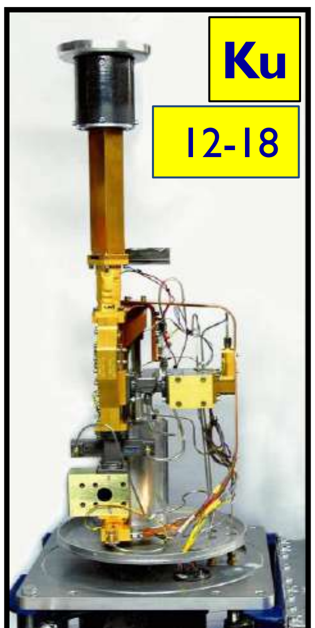


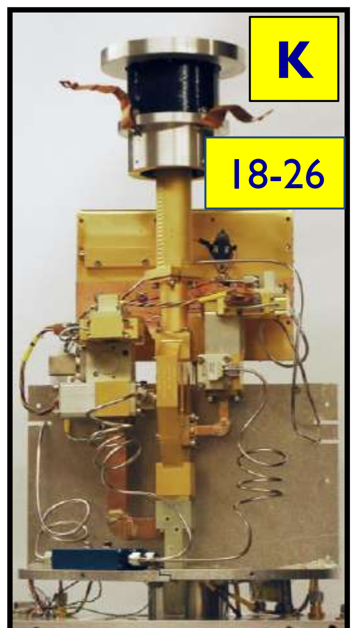
Rogues Gallery of (Naked) JVLA Receivers

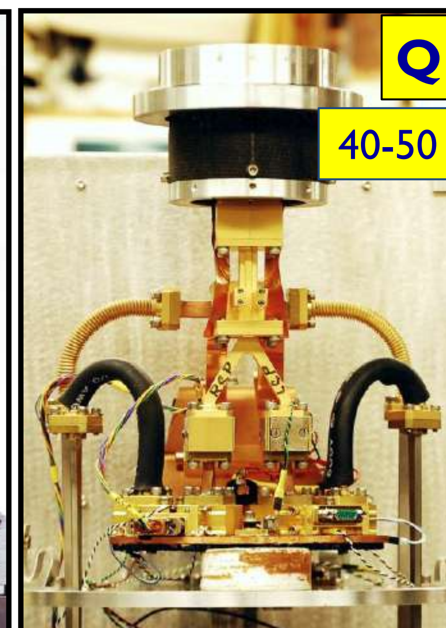








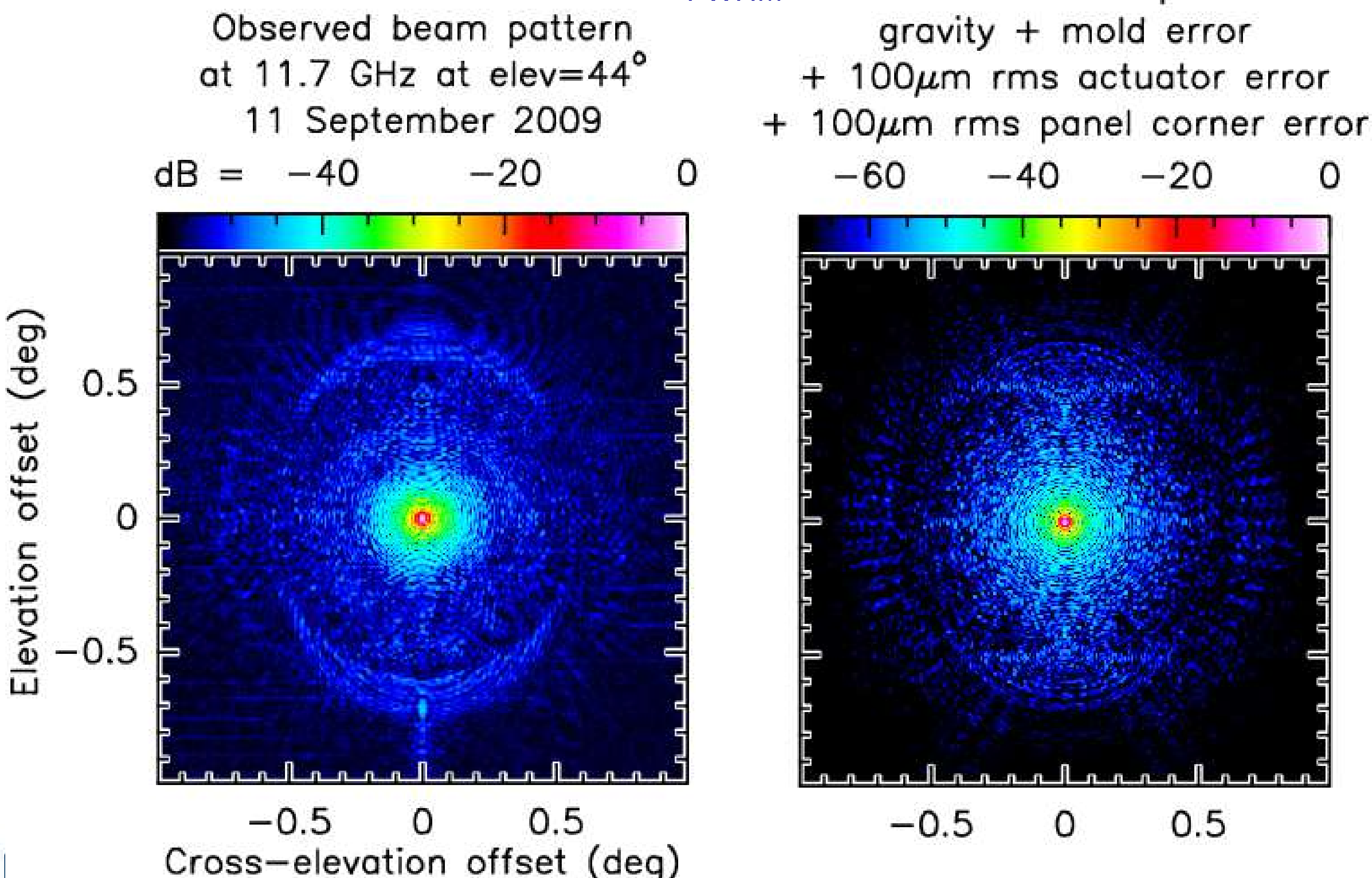




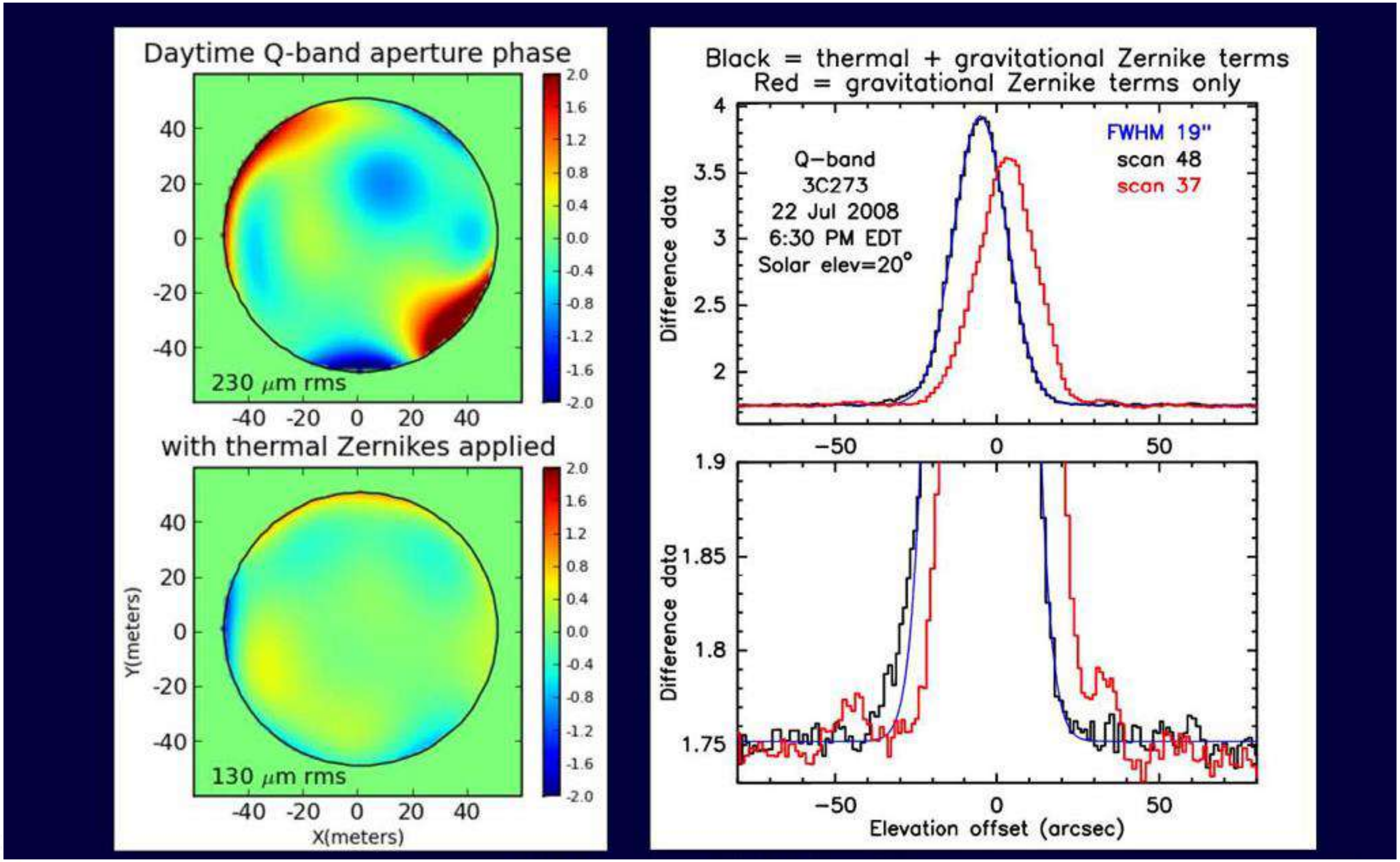
http://www.aoc.nrao.edu/~pharden/fe/fe.htm

Holography: effect of GBT panel mold error

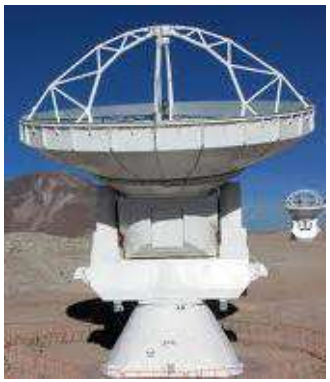
Panel size ~2m, error beam ~50 θ_{FWHM}

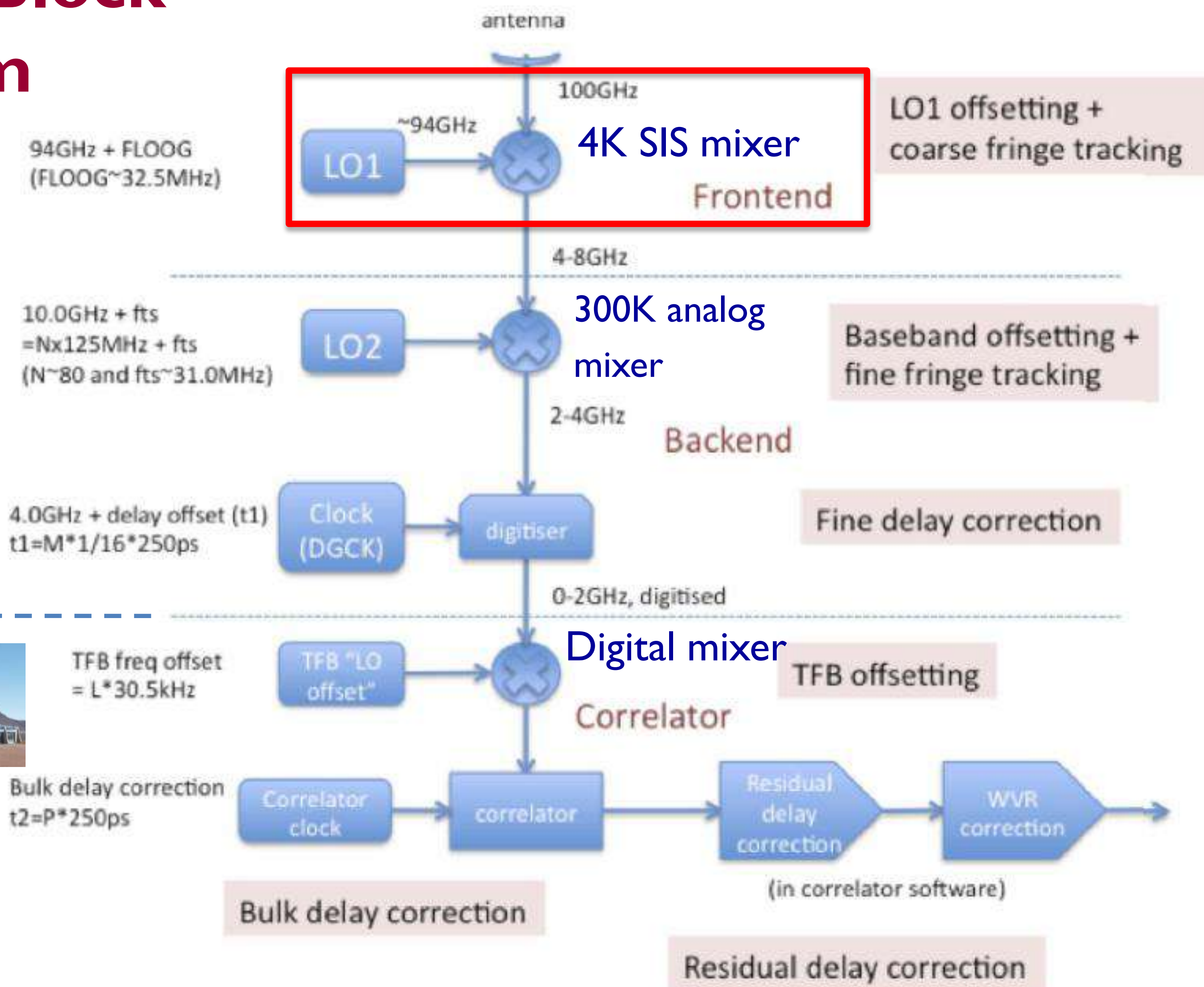


Holography: measuring and correcting the daytime distortion of GBT



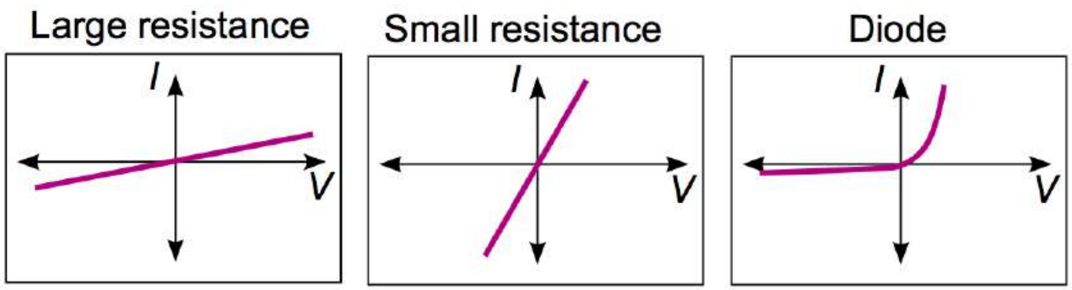
ALMA Block Diagram

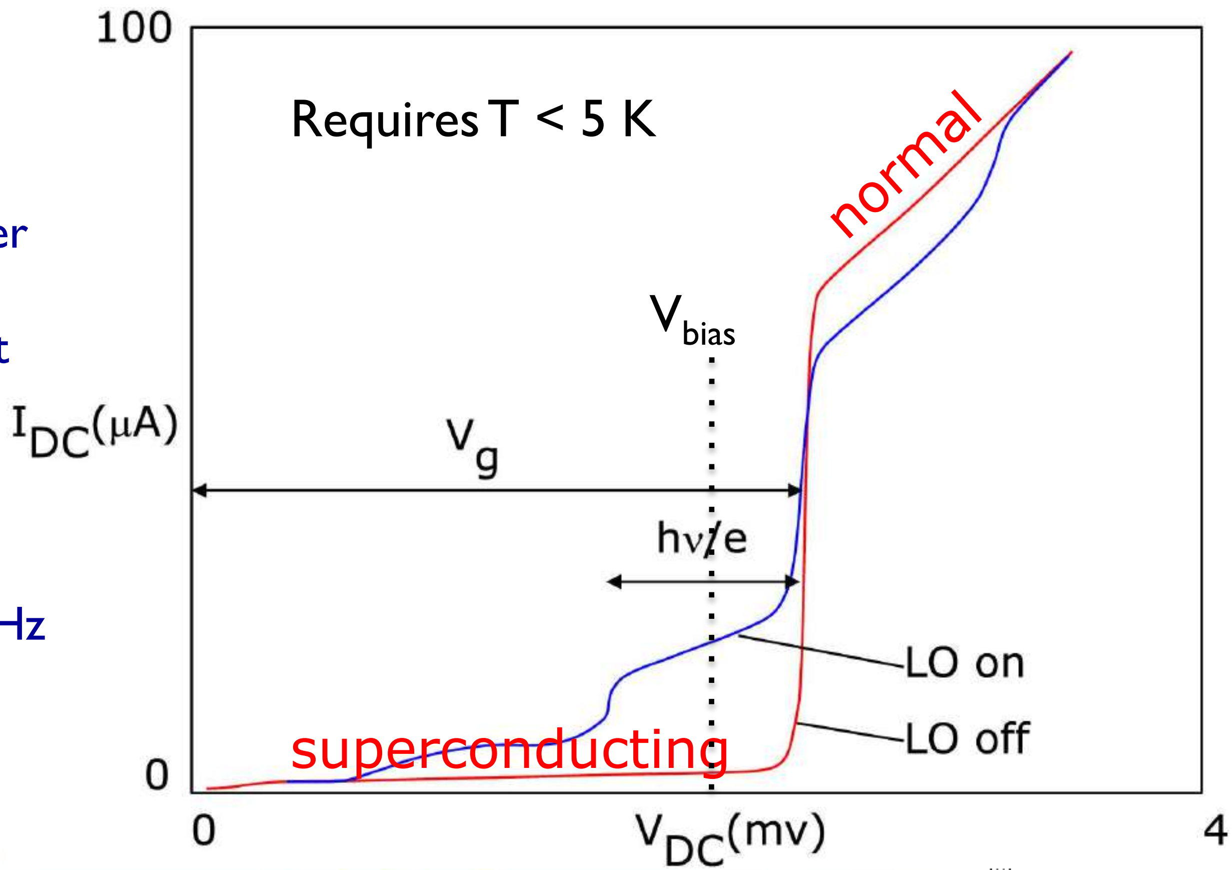




SIS mixer
I/V curve

1. Resistor: Ohm's law
2. Diode: Shockley's law
   "Non-linear" device
3. SIS tunneling junction:
   I=0 below gap voltage
   Photons can break Cooper pairs of electrons and create tunneling current
   230 GHz = 0.8 meV
   V_{gap}(Nb) ~2.9mV
   Vbias ~ 2.5mV
   f_{gap}(Nb)=(V_{gap})e/h=700 GHz
   f>f_{gap} degrades T_{rx}



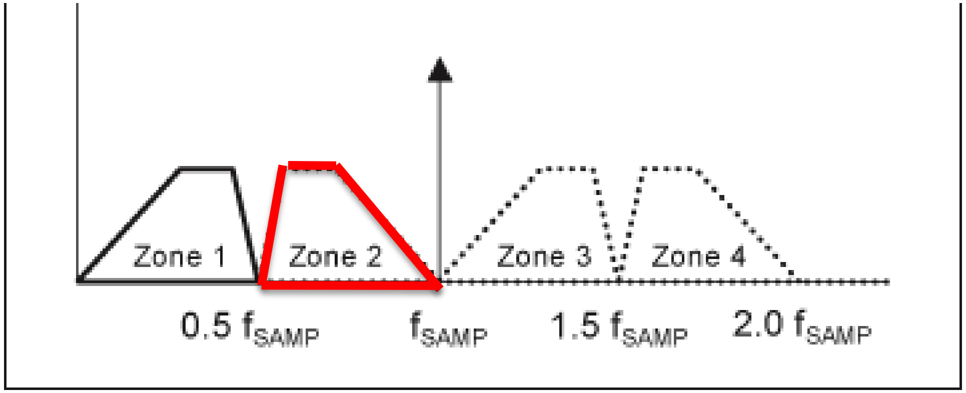


Digitizers and Nyquist zones

Nyquist theory:

F_{sample} >= 2*Bandwidth

ALMA & VLA sample in Nyquist Zone 2:



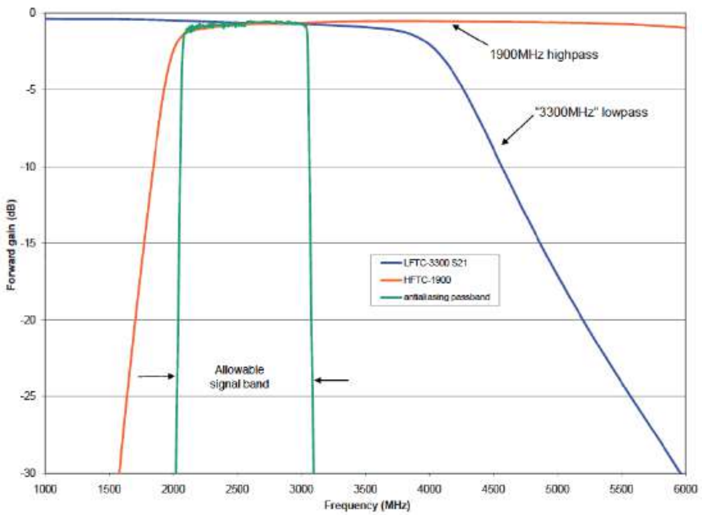
ALMA: 2-4 GHz (4.0 Gsample/sec) x 4 of them x 2 pols

JVLA: 1-2 GHz (2.048 Gsample/sec, 8-bit digitizers) x 2 of them x 2 pols

2-4 GHz (4.096 Gsample/sec, 3-bit digitizers) x 4 of them x 2 pols

Anti-aliasing bandpass filters

are essential to prevent leakage from adjacent Nyquist zones.



Measurement of T_{sys} in the Sub(millimeter)

The "chopper wheel" method: putting an ambient temperature load (T_{load}) in front of the receiver and measuring the resulting power compared to power when observing sky T_{atm} (Penzias & Burrus 1973).

Load in	$V_{in} = G\,T_{in} = G\,[T_{rx} + T_{load}]$
Load out	$V_{out} = G\,T_{out} = G\,[T_{rx} + T_{atm}(1\text{-}e^{-\tau}) + T_{bg}e^{-\tau} + T_{source}e^{-\tau}\,]$

assume $T_{atm} \approx T_{load}$

Comparing in and out: $$\frac{V_{in} - V_{out}}{V_{out}} = \frac{T_{load}}{T_{sys}}$$

$$\boxed{T_{sys} = T_{load} * T_{out} / (T_{in} - T_{out})}$$

Power is really observed but is $\propto$ T in the R-J limit

SMA calibration load swings in and out of beam

- If $T_{atm} \approx T_{load}$, and T_{sys} is measured often, changes in mean atmospheric absorption are corrected. ALMA has a two temperature load system which allows a measure of T_{rx}

ALMA Amplitude Calibration Device