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
Reflector antennas

GMRT

VLA, ALMA

SMA

Prime Focus

Offset Cassegrain

Nasmyth

Bent Nasmyth

Dual offset Gregorian

On-axis Cassegrain (best for array receivers)

ATCA, Mopra

CARMA, CSO

GBT

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

Receivers do not tilt in elev.
Reflector antenna efficiencies

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

Effective area (on-axis): \( A_0 = \eta A = (\text{aperture efficiency})(\pi R^2) \)

where \( \eta = \eta_{\text{surface}} \eta_{\text{blockage}} \eta_{\text{spillover}} \eta_{\text{taper}} \eta_{\text{radiation}} \eta_{\text{misc}} \)

\[
\eta_{\text{surface}} = \exp\left(-\left(\frac{4\pi \sigma}{\lambda}\right)^2\right) \quad \sigma = \text{rms surface error (Ruze 1966)}
\]

\[
= 0.44 \text{ for } \sigma = \lambda/14 \quad (\text{VLA at } 43 \text{ GHz})
\]

\[
= 0.79 \text{ for } \sigma = \lambda/26 \quad (\text{VLA at } 22 \text{ GHz})
\]

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

\( \eta_{\text{spillover}} = \text{feed spillover efficiency} \)

\( \eta_{\text{taper}} = \text{feed taper efficiency} \)

\( \eta_{\text{radiation}} = \text{metal reflection efficiency (} \approx 0.99 \text{ per Al mirror)} \)

\( \eta_{\text{misc}} = \text{diffraction, phase, focus error, polarization efficiencies} \)

\( \eta_{\text{illumination}} = 0.8 \text{ for } -10\text{dB taper} \)
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?

Fourier transform pairs
Uniform Antenna illumination: VLA

- Shaped symmetric primary, shaped asymmetric secondary
- Close to Airy disk (FWHM~1.028 λ/D) (radius of 1\textsuperscript{st} 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: \( \theta_{\text{FWHM}} = 1.13 \frac{\lambda}{D} \)
- Baars* (2007) and ALMA Memo 456 give numerical formulas relating FWHM to taper:

\[
\tau = 10^{\frac{\text{taper}}{20}} \\
\theta_{\text{FWHM}} = (1.243 - 0.343\tau + 0.12\tau^2) \frac{\lambda}{D}
\]

*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)
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 $V(\theta, \theta')$

$V(\theta, \theta') = \sum_{x,y} \exp[i(\psi_x(\theta, \theta') - \psi_y(\theta, \theta'))]$
What do holography data look like?

Example:

SMA at 232 GHz

Amplitude

Phase

Fourier transform

Beam map (angle units)

Aperture map (distance units)

ELEVATION

AZIMUTH
Holography: ALMA surface panel adjustment

Phase map converted to path length error from ideal paraboloid

Before adjustment (43\(\mu\)m)  After adjustment (11\(\mu\)m)
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.
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](image1.png)  ![Band 6 OMT (opened)](image2.png)

2) **Quasioptical** (i.e. in front of feed): Wire grid
   - Advantage: easier to construct for high freq.
   - Disadvantage: Alignment tricky ("squint" ~θ/10)

VLA S-band (2-4 GHz)
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)

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

Gain Elevation Dependence

Normalized Antenna Axial Gain

Antenna Elevation (deg.)

- 0.87mm
- 1.3mm
- 2mm
- 3mm
Antenna pointing and tracking

Static errors: Blind pointing vs. offset pointing
• ALMA: blind=2”, offset=0.6” rms ($\theta_{\text{FWHM}}/10$ at Band 10)
• VLA: blind~15”, offset=3” rms ($\theta_{\text{FWHM}}/17$ at 50 GHz)

Dynamic errors: wind etc.
• VLA: tracking ~ 3” rms (no wind)
  i.e. peak excursions +6”
$\theta_{\text{FWHM}}/10$ at 43 GHz

How good is $\theta_{\text{FWHM}}/10$?
not very good away from the beam center!
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
Detail of velocity servo loop: PID type proportional / integral / derivative

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

<table>
<thead>
<tr>
<th>Wavelength Band (letter code)</th>
<th>Nominal frequency range (GHz)</th>
<th>Polarization, operating temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 m (4)</td>
<td>0.058-0.084</td>
<td>Linear, 300K</td>
</tr>
<tr>
<td>90 cm (P)</td>
<td>0.23-0.47</td>
<td>Linear, 300K</td>
</tr>
<tr>
<td>20 cm (L)</td>
<td>1.0-2.0</td>
<td>Circular, 15K</td>
</tr>
<tr>
<td>13 cm (S)</td>
<td>2.0-4.0</td>
<td>Circular, 15K</td>
</tr>
<tr>
<td>6 cm (C)</td>
<td>4.0-8.0</td>
<td>Circular, 15K</td>
</tr>
<tr>
<td>3 cm (X)</td>
<td>8.0-12.0</td>
<td>Circular, 15K</td>
</tr>
<tr>
<td>2 cm (Ku)</td>
<td>12.0-18.0</td>
<td>Circular, 15K</td>
</tr>
<tr>
<td>1.3 cm (K)</td>
<td>18.0-26.5</td>
<td>Circular, 15K</td>
</tr>
<tr>
<td>1 cm (Ka)</td>
<td>26.5-40.0</td>
<td>Circular, 15K</td>
</tr>
<tr>
<td>0.7 cm (Q)</td>
<td>40.0-50.0</td>
<td>Circular, 15K</td>
</tr>
</tbody>
</table>
**ALMA receiver summary (dual linear pol.)**

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

* under development

[Image of ALMA receiver]
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 **2-port** devices: one input and one output

\[
\text{IN} \rightarrow \text{OUT} \quad (10-30\text{dB stronger, same frequency})
\]

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

- Operate at \(~15\text{ K}\)
- \(T_{\text{noise}} \sim 5\text{ hf/k}\)
  (i.e. \(~5\times\text{ quantum limit}\))
- M. Pospieszalski (2012)
  (MIKON conference)
What is a mixer?

Mixers are 3-port 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 transfer the phase from the RF to the IF 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)

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

Image of SIS junction from Electron Microscope (Hedden et al. 2010)
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 interferometry)
SSB: VLA receivers

**Power (dBm)**

- **IF Out**: 8-18 GHz
- **Ka-Band Rx**: 26-40 GHz
- **LO = 46 GHz**

![Graph showing frequency ranges and power levels for VLA receivers](image)

**2SB: ALMA Bands 3-8**

- **LO = 341 GHz**
- **Single Continuum**
- **CO v=0 3-2**
- **LSB**: 2 pols
- **USB**: 2 pols

![Graph showing frequency ranges and polarization for ALMA bands](image)

Band 7: Meier et al 2005
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:

$$P_{out} \propto V_{out} = G \cdot (T_{input} + T_{rx})$$

Unknown slope  
Calibrated ‘load’  
Receiver temperature

Power detector $P \propto V$  
$\Rightarrow$ 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  
$y = mx + b$

Define the “$Y$” factor

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

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

$G[\text{Volt/Kelvins}] = \frac{[V_{RX} + V_{HOT}]}{T_{HOT}} \cdot \frac{[V_{RX} + V_{COLD}]}{T_{COLD}}$
ALMA Sensitivity: Band 6 (230 GHz)

- Autocorrelation spectra from $T_{\text{sys}}$ scan
- Note 3dB IF power variation vs. freq
- Shape is removed from cross-correlation

$T_{RX}$: receiver sensitivity

$T_{SYS}$: system sensitivity

$O_3$ line
T(Rx) vs. Frequency for JVLA Receiver Bands

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

<table>
<thead>
<tr>
<th>Band</th>
<th>L</th>
<th>S</th>
<th>C</th>
<th>X</th>
<th>Ku</th>
<th>K</th>
<th>Ka</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{Rx}</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>20</td>
<td>25</td>
<td>34</td>
<td>40</td>
<td>48</td>
</tr>
</tbody>
</table>

Simple T(Rx) Noise Model

T(Rx) = m \cdot F + b

where m = 1^\circ K / GHz, b = 8^\circ K for 1→4 GHz

where m = 0.5^\circ K / GHz, b = 2^\circ K for 4→50 GHz

Simple Noise Model

T(Rx) = m \cdot F + b

where m = 1^\circ K / GHz, b = 8^\circ K for 1→4 GHz

where m = 0.5^\circ K / GHz, b = 2^\circ K for 4→50 GHz
Radiometer equation derivation & simulation

1. Consider a sample time series of an RF signal: $x_n \sim N$ (mean=0, variance=$\sigma^2$)
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. $x_n^2 = \sigma^2 Z_n^2 = \Gamma(1/2, 2\sigma^2) = \text{the gamma distribution (c.f. constant \times Chi square)}$
   with expectation mean = $\mu_{\text{gamma}} = \sigma^2$, and expectation variance = $\sigma_{\text{gamma}}^2 = 2\sigma^4$
Radiometer equation derivation

5. The Nyquist sample rate is twice the bandwidth \((2\beta)\) and the time interval of the data is \(\tau\), 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 
\((1/N) \sum x_n^2\) will have a distribution variance of 
\[\sigma_p^2 = 2\sigma^4/N = 2\sigma^4/(2\beta\tau) = \sigma^4/(\beta\tau)\]
and thus its standard deviation is 
\[\sigma_p = \sigma^2/\sqrt{(\beta\tau)}\]

7. Substitute \(\mu_{\text{gamma}}\) (from Step 4) for \(\sigma^2\) in the numerator: 
\[\sigma_p = \mu_{\text{gamma}}/\sqrt{(\beta\tau)}\]

**NOTE:** \(\mu_{\text{gamma}}\) 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 \(G = \text{gain}\))
Thus, 
\[\sigma_p/P = \sigma_T/T\] and 
\[\sigma_T = T/\sqrt{(\beta\tau)}\] independent of Gain!

Recall the input power level was 4!

*Recall the input power level was 4!*

\(\mu_{\text{gamma}}\) is the expectation mean of \(x_n^2\) and is equivalent to the sample mean power \(P\) for large \(N\).
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

1. Antenna position loop ~ 5 Hz
2. Motor velocity loop ~ 100 Hz
3. Motor current loop ~ few kHz

Position and Velocity request

Microcontroller board

DAC

ADC

System State
Velocity Command

Limit switches

Motor

Tachometer

ADC

Position Feedback

Velocity Feedback

Servo Motor

Resolver

Tach

22 Bit Encoder

ADC

Torque Command

System State Info

ADC

Velocity Command

System State

Position and Velocity request

New Mexico CONSORCIO
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
World’s best LNA’s from CDL

http://www.aoc.nrao.edu/~pharden/fe/fe.htm
Holography: effect of GBT panel mold error

Panel size ~2m, error beam ~50 \( \theta_{\text{FWHM}} \)

Observed beam pattern at 11.7 GHz at elev=44°
11 September 2009

dB = -40 -20 0

Theoretical beam pattern:
- gravity + mold error
- + 100\(\mu\)m rms actuator error
- + 100\(\mu\)m rms panel corner error

-60 -40 -20 0

NRAO

Fourteenth Synthesis Imaging Workshop
Holography: measuring and correcting the daytime distortion of GBT
ALMA Block Diagram

4K SIS mixer
300K analog mixer
Digital mixer
**SIS mixer**

**I/V curve**

1. Resistor: Ohm’s law
2. Diode: Shockley’s law
   “Non-linear” device
3. SIS tunneling junction:
   \[ I = 0 \text{ below gap voltage} \]
   Photons can break Cooper pairs of electrons and create tunneling current

\[ 230 \text{ GHz} = 0.8 \text{ meV} \]

\[ V_{\text{gap}}(\text{Nb}) \approx 2.9 \text{ mV} \]

\[ V_{\text{bias}} \approx 2.5 \text{ mV} \]

\[ f_{\text{gap}}(\text{Nb}) = \frac{V_{\text{gap}}}{e/h} = 700 \text{ GHz} \]

\[ f > f_{\text{gap}} \] degrades \( T_{\text{rx}} \)

**Diagram:**

- **Large resistance**
- **Small resistance**
- **Diode**

**Graph:**

- Requires \( T < 5 \text{ K} \)
- \( V_{\text{bias}} \)
- \( V_{g} \)
- \( h \nu/e \)

**Legend:**

- **LO on**
- **LO off**

**New Mexico CONSORTIUM**
Digitizers and Nyquist zones

Nyquist theory:
\[ F_{\text{sample}} \geq 2 \times \text{Bandwidth} \]

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).

\[
V_{in} = G \ T_{in} = G \ [T_{rx} + T_{load}]
\]

\[
V_{out} = G \ T_{out} = G \ [T_{rx} + T_{atm}(1-e^{-\tau}) + T_{bg}e^{-\tau} + T_{source}e^{-\tau}]
\]

Assume \( T_{atm} \approx T_{load} \).

Comparing in and out

\[
\frac{V_{in} - V_{out}}{V_{out}} = \frac{T_{load}}{T_{sys}}
\]

\[
T_{sys} = T_{load} * \frac{T_{out}}{(T_{in} - T_{out})}
\]

Power is really observed but is \( \propto T \) in the R-J limit.

- 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

- Calibration Loads
- Solar Filter
- Robotic Arm
- Cryostat
- Top
- Plate
- Calibration Wheel
- QWP translation unit
- Structure

Calibration Loads controller