3 hardware lectures

1. receivers - SIS mixers, amplifiers, cryogenics, dewars, calibration; followed by antenna tour; later, take apart a 6-m dewar
2. correlator (James Lamb)
3. local oscillator system - Gunn oscillator, phaselock chain, linelength system, lobe rotation, sideband separation

receivers

- radiation collected by the telescope is focused onto a ‘feed horn’ that couples it into a waveguide
- the receiver amplifies and converts some frequency range of the incoming signals to a lower frequency ‘IF’ (intermediate frequency) that is sent back to the control building

suppose we observed a 10 Jy calibrator with CARMA for 1 year, 24 hrs/day – how much energy would we collect?

$$E = \frac{1}{2} S \eta A \Delta\nu\ t$$

- S = source flux density = 10 Jy = 10 x 10^{-26} watts m^{-2} Hz^{-1}
- the factor of ½ arises because we are sensitive to 1 polarization
- η = aperture efficiency ~ 0.60
- A = geometrical collecting area = 6 x 85 m^2 + 9 x 29 m^2 = 771 m^2
- Δν = instantaneous bandwidth = 2 x 4.0 GHz = 8 x 10^9 Hz
- t = 1 year = 3 x 10^7 sec

Result: E = 5.6 x 10^{-6} joules

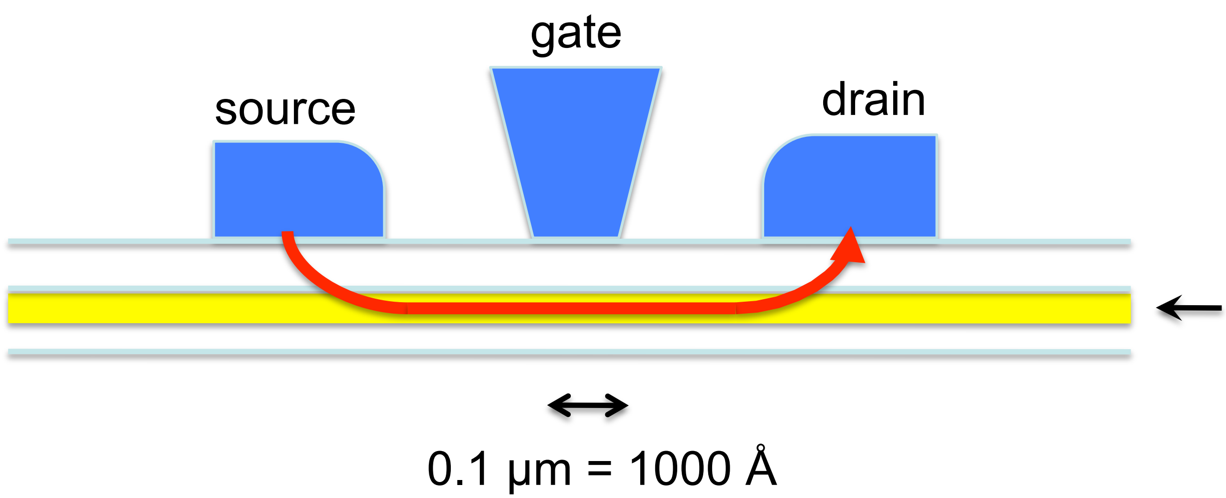
1 calorie = 4.2 joules heats 1 cm^3 (20 drops?) of water by 1 C

➔ must observe for 38000 years to heat 1 drop of water by 1 C

detectors for radio astronomy

1. bolometers
   - absorbed photon increases temperature, changes resistance
   - phase of incoming signal is lost – unsuitable for aperture synthesis
   - operate at ~0.3 K
2. HEMT (High Electron Mobility Transistor) amplifiers
   - preferred below 50 GHz, good up to 115 GHz
   - operate at ~20 K
3. SIS mixers
   - mixes incoming signal with local oscillator to convert it to a lower frequency where it is amplified (by HEMT)
   - preferred for 100+ GHz
   - operate at ~4 K

High Electron Mobility Transistor (HEMT) amplifier



in HEMT (but not in FET), current travels through very pure layer -> no scattering by impurities

- gate voltage controls width of channel, modulates current from source to drain
- to operate at 100 GHz, charge carriers must transit under the gate in ~ 1/10 x 1/100 GHz ~ 10^{-12} sec
- must travel 0.1 um in 10^{-12} sec ~ 100 km s^{-1}

mixers are used to convert signals to a lower frequency

- ‘mix’ RF (radio frequency) signal with a strong LO (local oscillator) to produce an IF (intermediate frequency)
- e.g., 102 GHz RF + 100 GHz LO -> 2 GHz IF (also, 98 GHz RF + 100 GHz LO -> 2 GHz IF)
- can be thought of as ‘sampling’ the incoming signal; local oscillator is the clock

mixer has a nonlinear current-voltage relation

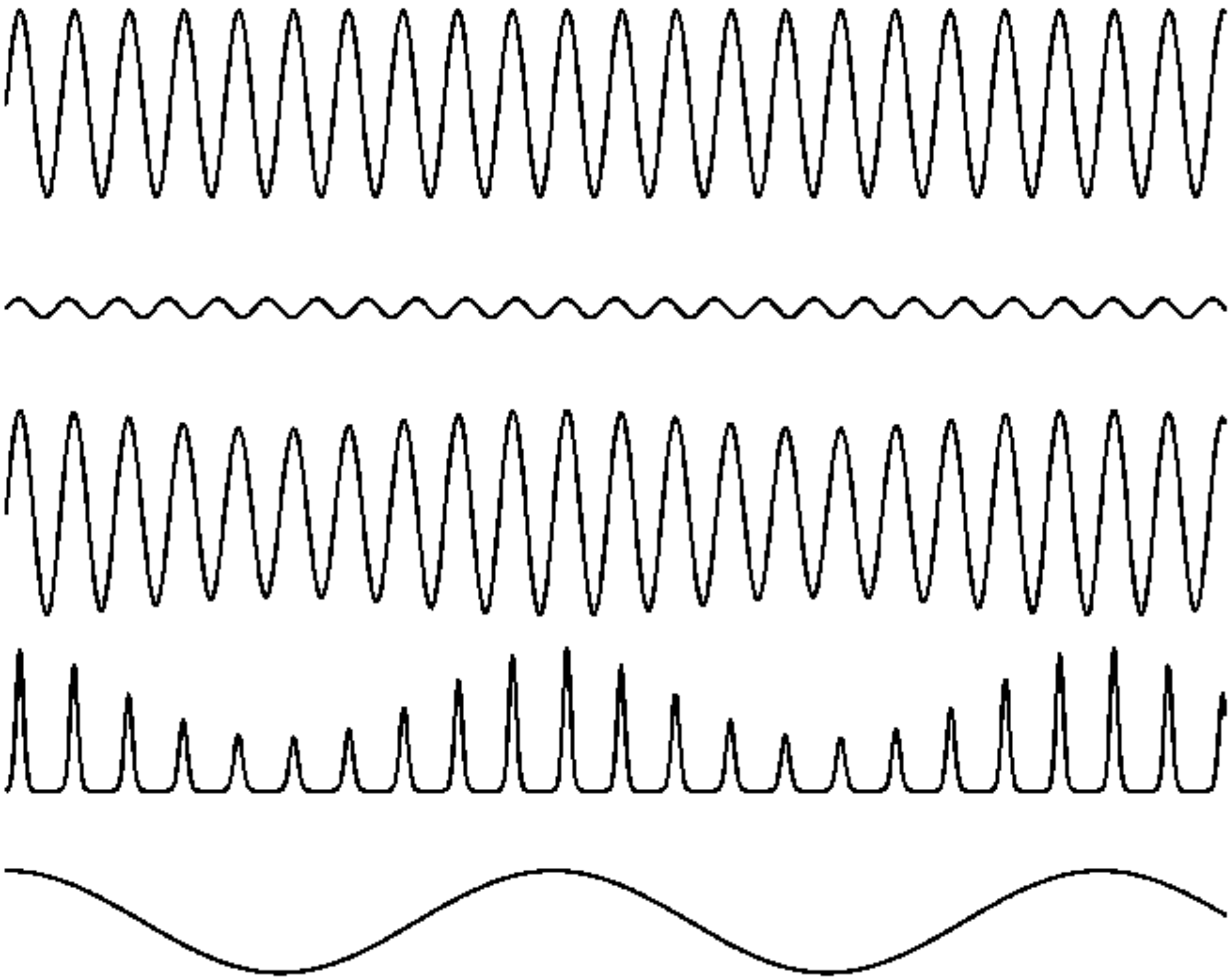
- linear device (superposition principle):
  $\omega_1, \omega_2 \rightarrow$ [linear device] $\rightarrow \omega_1, \omega_2$
- nonlinear device:
  $\omega_1, \omega_2 \rightarrow$ [nonlinear device] $\rightarrow \omega_1, \omega_2, \omega_1+\omega_2, \omega_1-\omega_2, 2\omega_1+\omega_2, \ldots$
- diode is an example of a nonlinear device:

  $I = I_0(e^{\alpha V} - 1) \sim I_0(\alpha V + ½\, \alpha^2 V^2 + ..)$

  $V = A \cos\omega_1 t + B \cos\omega_2 t$

  $V^2 = A^2 \cos^2\omega_1 t + B^2 \cos^2\omega_2 t + 2AB \cos\omega_1 t \cos\omega_2 t + \ldots$
  $= \;\ldots + AB \cos(\omega_1 + \omega_2)t + AB \cos(\omega_1 - \omega_2)t + \ldots$
- note: *amplitude* at frequency ω_1-ω_2 is *linearly* related to amplitudes A and B

waveforms



local oscillator (LO)

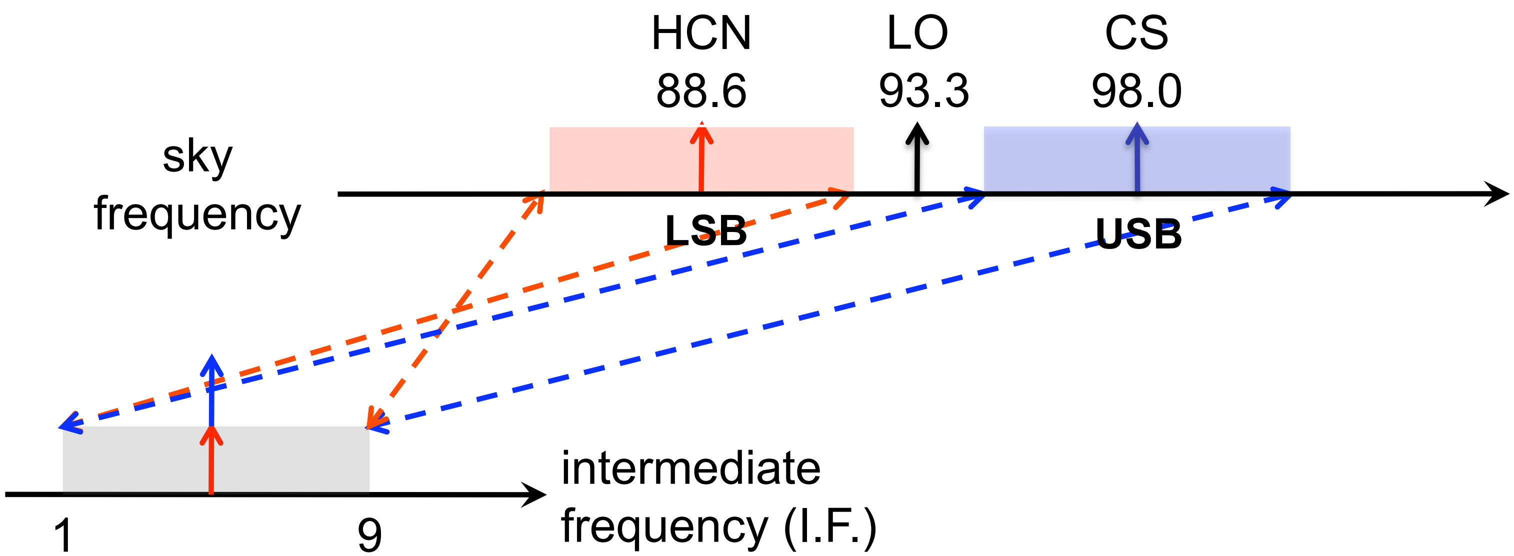
‘signal’ – just random noise for radio astronomy

LO + signal (voltage in diode)

current through diode

IF after low pass filtering

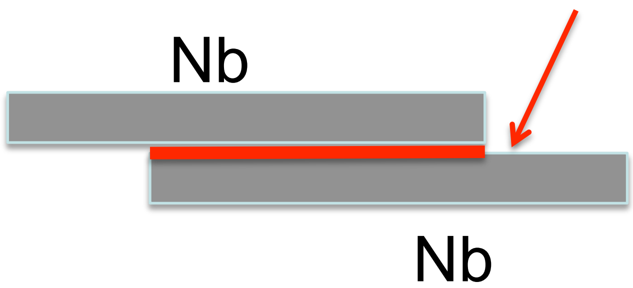
DSB (double sideband) downconversion



- upper and lower sidebands are folded together in the I.F. – e.g., HCN at 88.6 and CS at 98.0 both appear at 4.7 GHz in the I.F. – but can be separated by phase switching (lecture 3)
- LO tunable from 85-114 GHz (3mm) and 215-270 GHz (1mm)
- SZA 3mm receivers are different – USB only

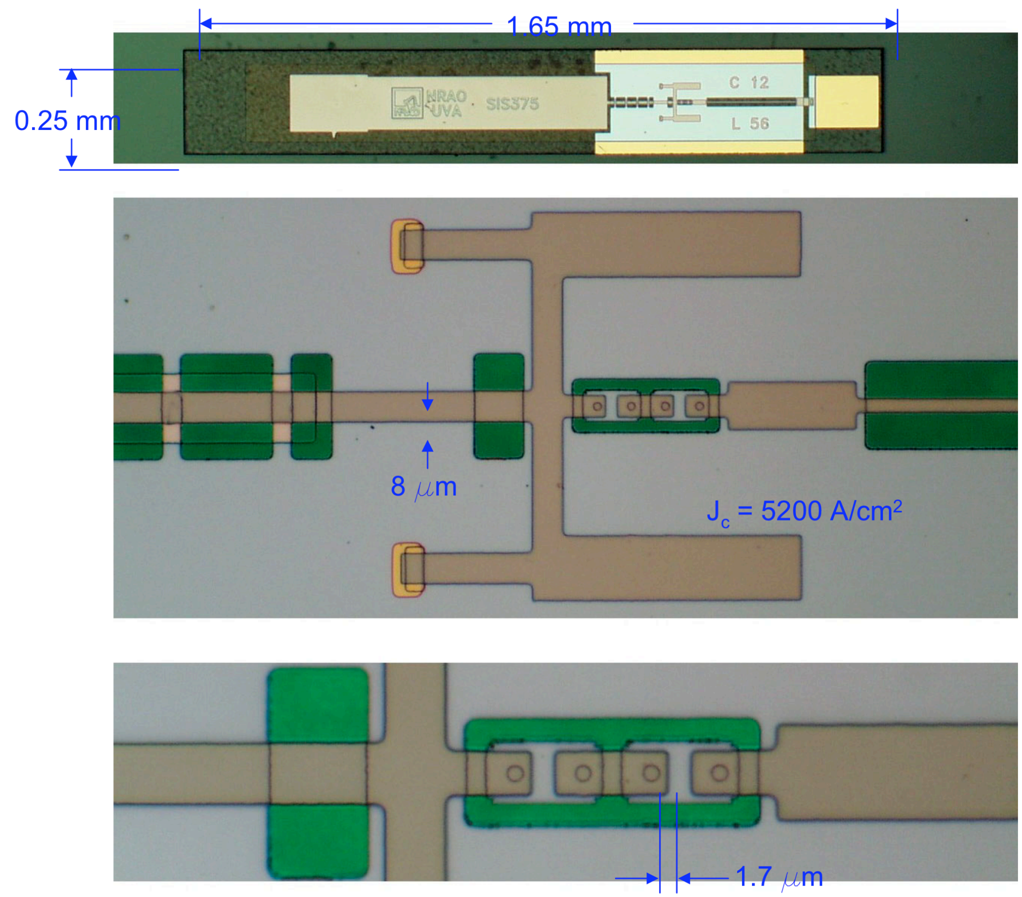
SIS (Superconductor-Insulator-Superconductor) tunnel junctions used as mixers at mm wavelengths

AlO insulating layer, 10Å thick



SIS junction cross section

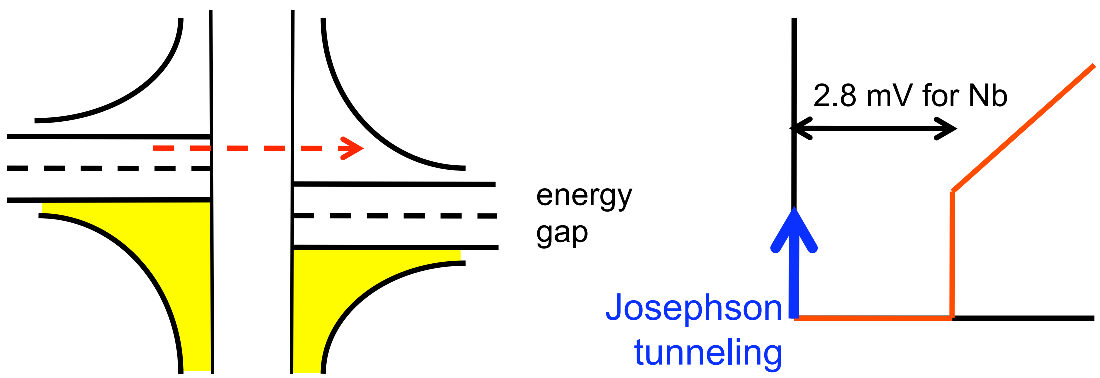
operate at
4 Kelvin



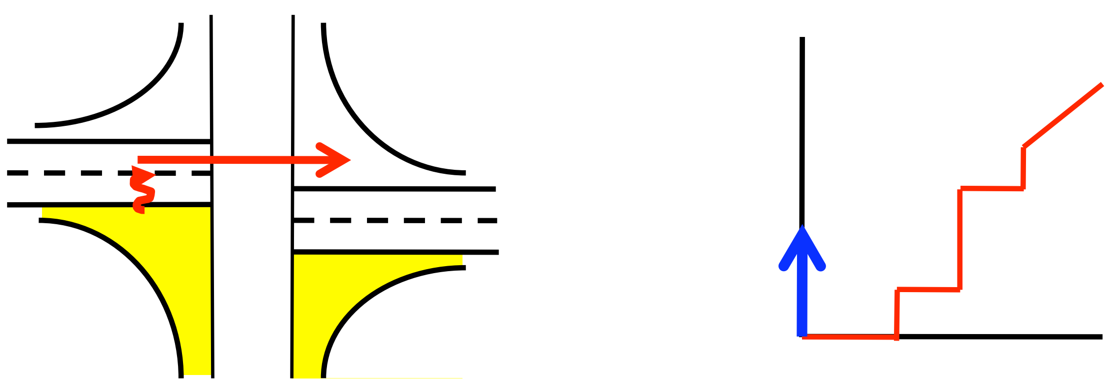
photographs of SIS device with matching circuitry

SIS devices have extremely sharp nonlinearity

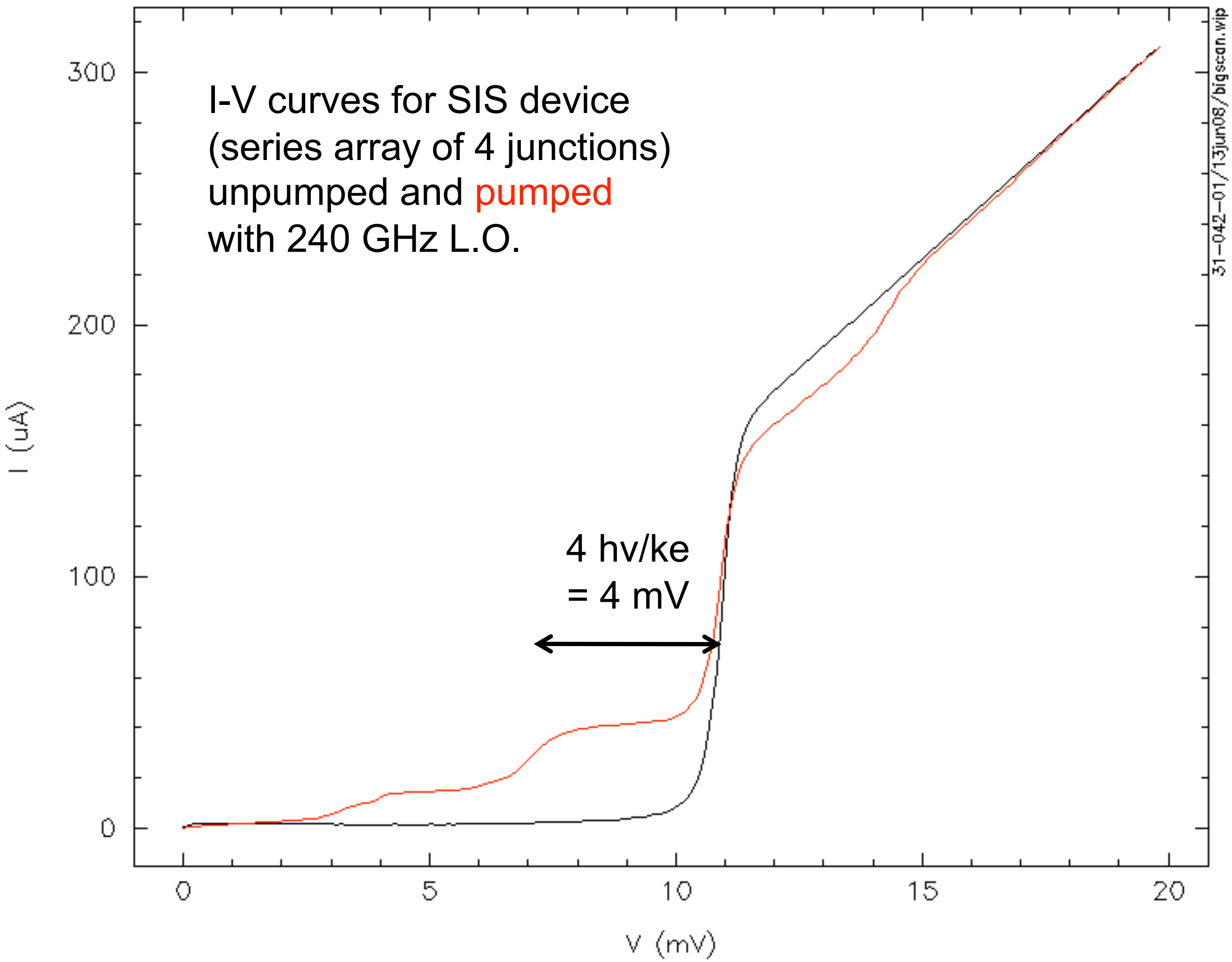
normal metal:
tunneling barrier
looks like a resistor



superconductor;
no single particle
current until
V > energy gap;
produces sharp
nonlinearity

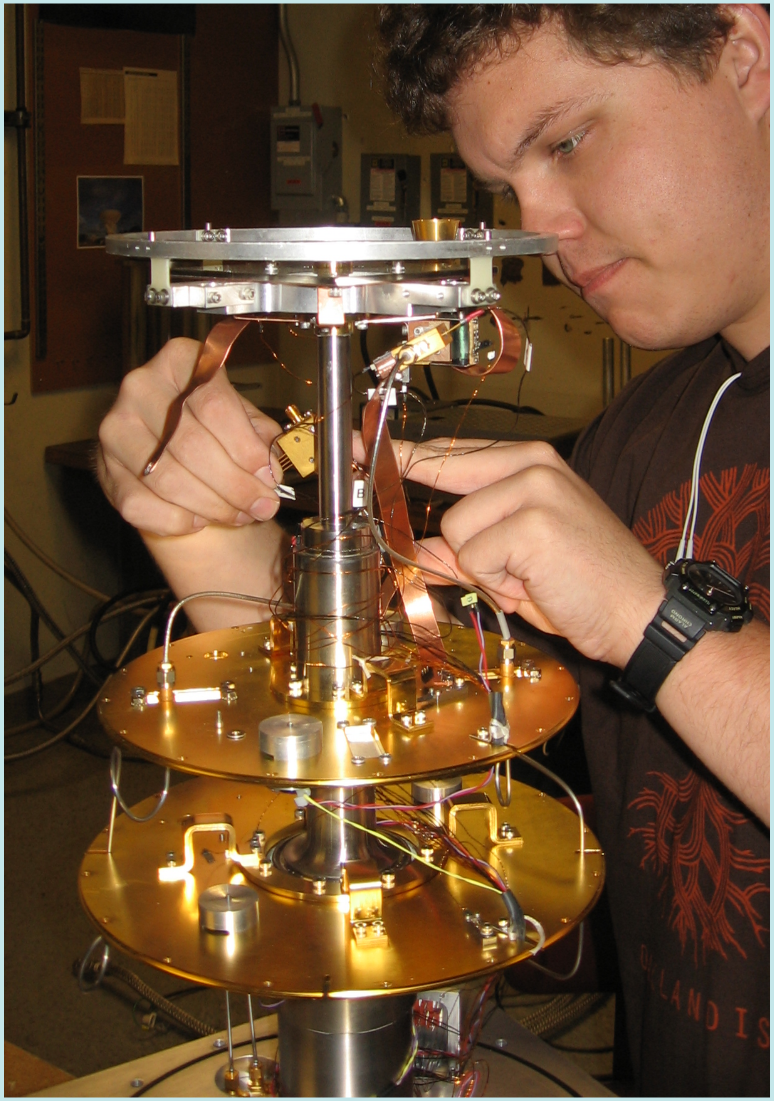


photon-assisted
tunneling across
barrier (1 meV= hν
for ν = 242 GHz)



I-V curves for SIS device
(series array of 4 junctions)
unpumped and pumped
with 240 GHz L.O.
4 hv/ke
= 4 mV
I (uA)
V (mV)
0
100
200
300
0
5
10
15
20
31-042-01/13jun08/bigscan.wip

cryocooler and dewar



closed cycle 4 K cryocoolers

- similar to Carnot cycle:
  - compress helium to ~280 psi, air-cool to remove heat of compression
  - in the ‘cold head,’ expand to ~60 psi to provide refrigeration
- except: use heat exchangers (bronze screens, Pb spheres, Er_3Ni spheres) in the cold head to reduce the pressure difference that is needed
- above the critical pressure of ~30 psi, 4 K helium does not separate into gas and liquid phases – it is a dense fluid

cryocoolers - practical details

- on 6-m antennas, must slow down the cold head cycle to get to lowest temperatures; 72 rpm during cooldown to 5 K, 30 rpm to operate at 3 to 3.8 K
- contaminants in helium gas stream ultimately freeze out at 4 K, lead to erratic operation; 5 minute defrost cycle can help; every 6-12 months warm to room temperature, flush with fresh helium
- oil is injected into gas stream in the compressors to absorb heat of compression; overheating most likely in extremely cold weather when oil gets viscous

dewar design

to minimize heat load on cryocooler:

- evacuate to minimize gas conduction; pressure < 10^{-9} atm, ~ a few x 10^{10} cm^{-3}
- use low thermal conductivity materials; a copper wire 24” long x .022” diam would conduct 50 mW from room temp to 4 K
- copper shields reduce loading from room temperature radiation (300 mW/sq in for a 300 K black body)

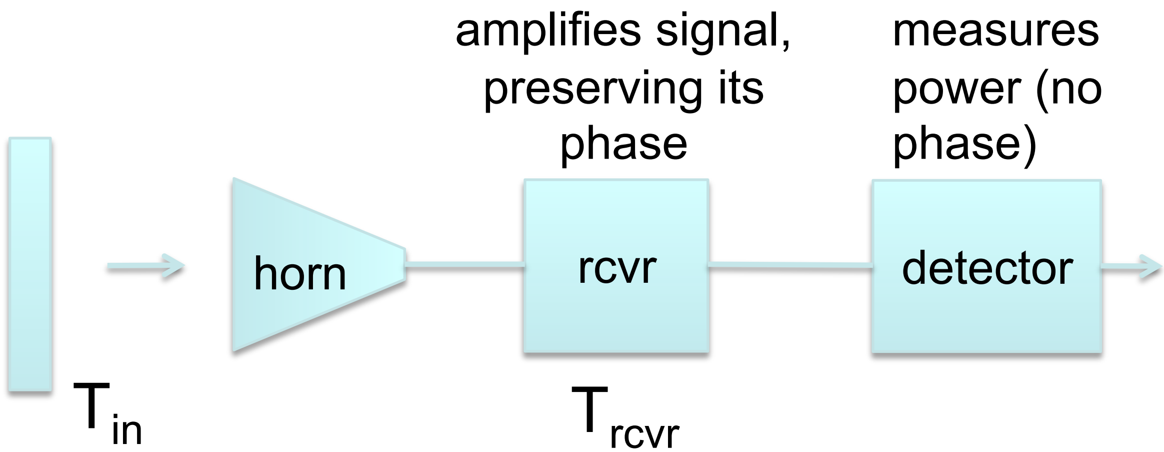
local oscillators

- LO = microwave signal on each receiver that ‘mixes’ with incoming radio signal
- LO frequency is tunable, determines what spectral chunks are sent back to the control building on the IF
- LOs must be perfectly synchronized on all telescopes – phaselocked to reference signals sent from the lab (a servo system; subject of hardware lecture 3)
- beamsplitters combine signal and LO

fiberoptic links

- signals between antenna and control building travel over glass fibers in underground conduits
- transmitter: intensity-modulated IR laser
- receiver: photodiode measures laser intensity
- 8 fibers per antenna: 2 Ethernet, 2 IF, 4 phaselock reference signals
- reconnect fibers in antenna base and in control building each time an antenna is moved

receiver calibration



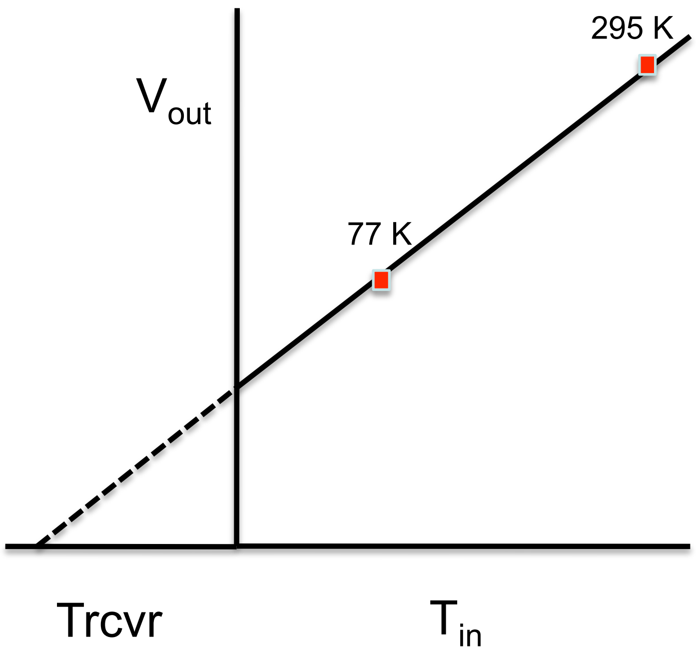
$V_{out} = G\,(T_{in} + T_{rcvr})$
(volts or counts)

- black body emitters are the most convenient calibration sources (K instead of ergs $cm^{-2}\ s^{-1}\ Hz^{-1}$); power collected in 1 polarization by horn with aperture D is:

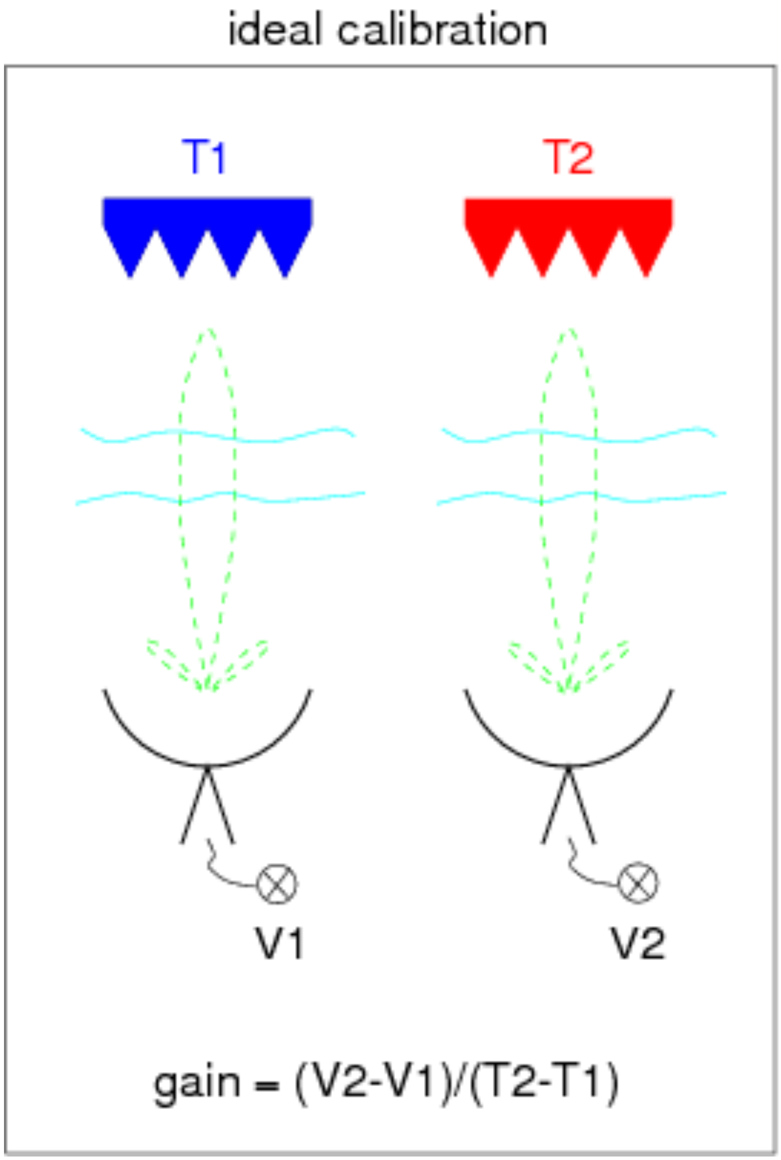
$$P_{in} = \frac{1}{2} B\ A\ \Delta\Omega\ \Delta\upsilon = \frac{1}{2}\frac{2kT}{\lambda^2} D^2 \frac{\lambda^2}{D^2}\Delta\upsilon = kT\Delta\nu$$

- T_{rcvr} is the noise generated by the receiver, referred to the input of the receiver

receiver calibration



- in the lab, use black body emitters at room temperature (295 K) and immersed in LN_2 (77K)
- solve for gain G and receiver temperature Trcvr
- Tsys = Tin + Trcvr is the total noise power from the receiver, calibrated as an input temperature

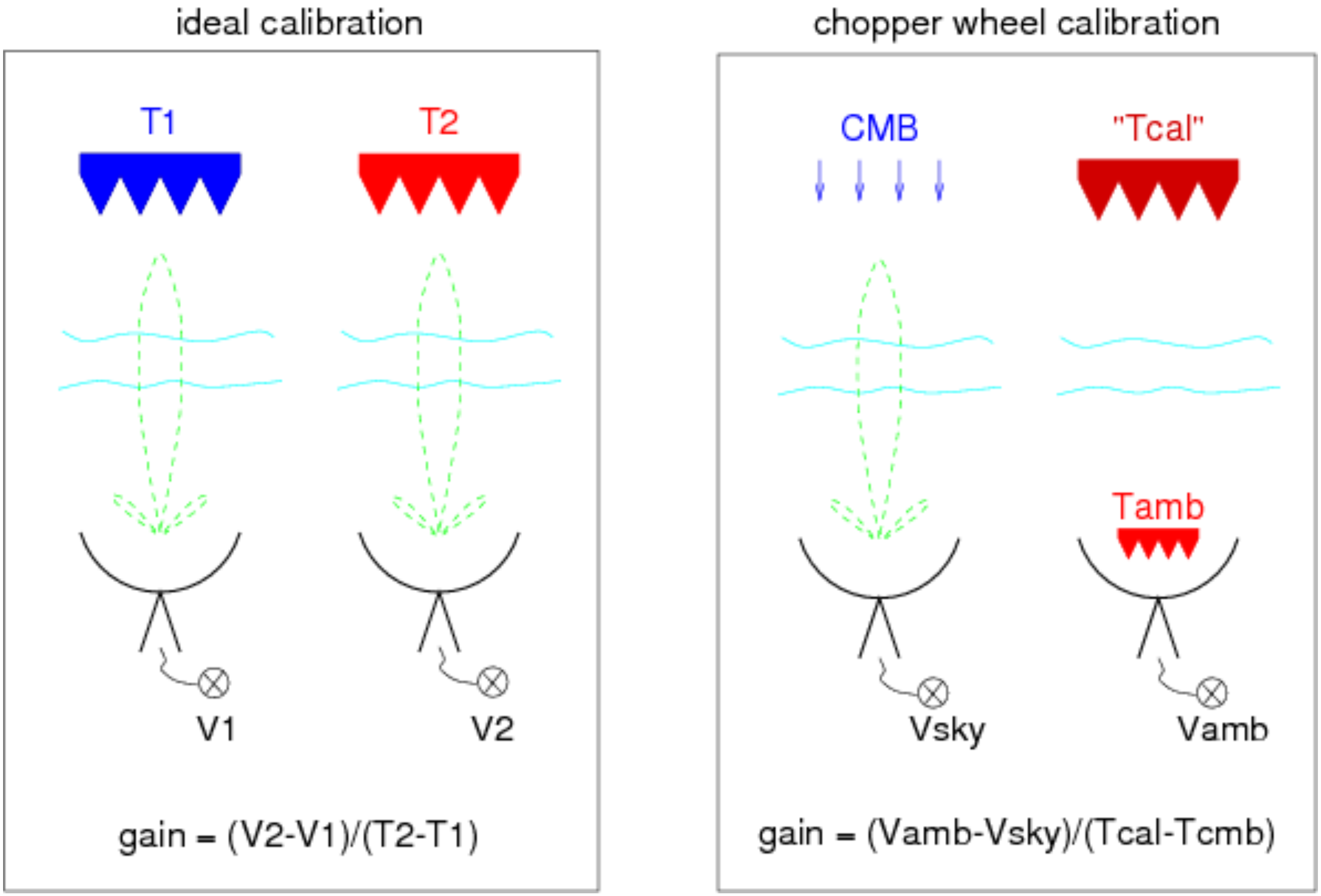


calibration for astronomical objects

- ideally, calibrate with loads outside the atmosphere
- unfurl a 200 x 200 m load from the space station?
- nature provides T_1 = CMB
- effective temperature of T_2 at the input to the receiver:

$$T_2' = T_2\, e^{-\tau} + T_{atm}(1 - e^{-\tau})$$

so if $T_2 = T_{amb}$, it doesn't matter where we position the load along the line of sight – it can be right in front of the receiver!


ideal calibration
T1
T2
V1
V2
gain = (V2-V1)/(T2-T1)
chopper wheel calibration
CMB
"Tcal"
Tamb
Vsky
Vamb
gain = (Vamb-Vsky)/(Tcal-Tcmb)

more notes on chopper wheel cal

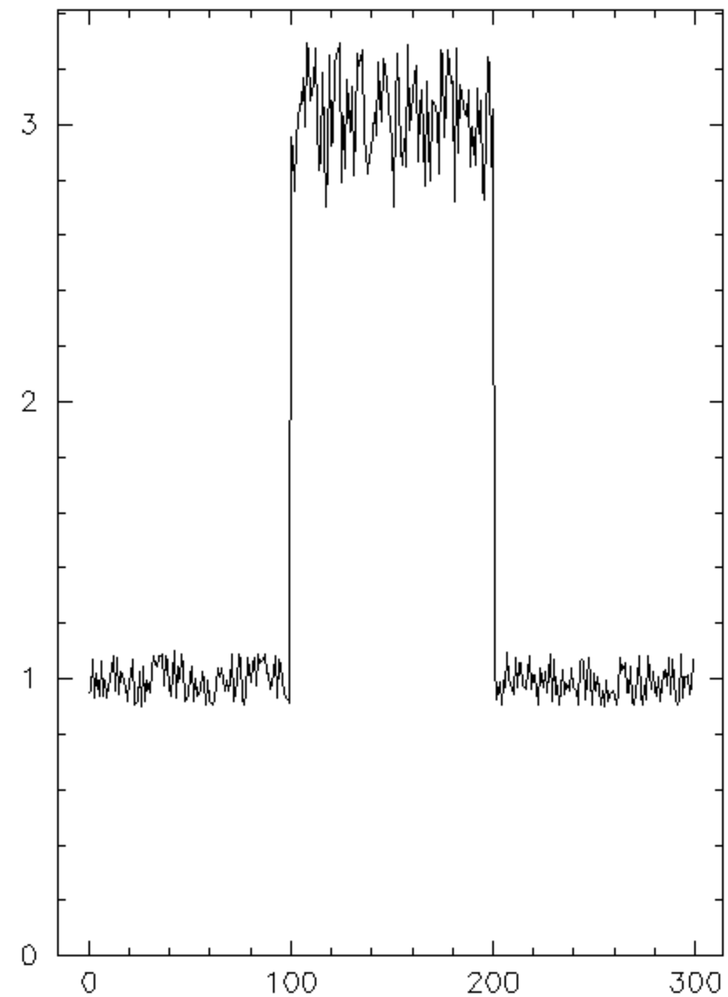
- effectively, we are including the atmosphere as part of the receiver: hence, we can't tell the difference between a poor receiver and a rainy day – both lead to high Tsys (but we have 15 antennas, so spotting bad rcvr is easy)
- as long as Tamb ≈ Tatm, the effective calibration temperature Tcal depends only weakly on the details of the atmospheric model
- receivers are sensitive to 2 bands (LSB and USB); normally Tsys(LSB) = Tsys(USB) = 2 × Tsys(DSB)
- reference: Ulich & Haas 1976

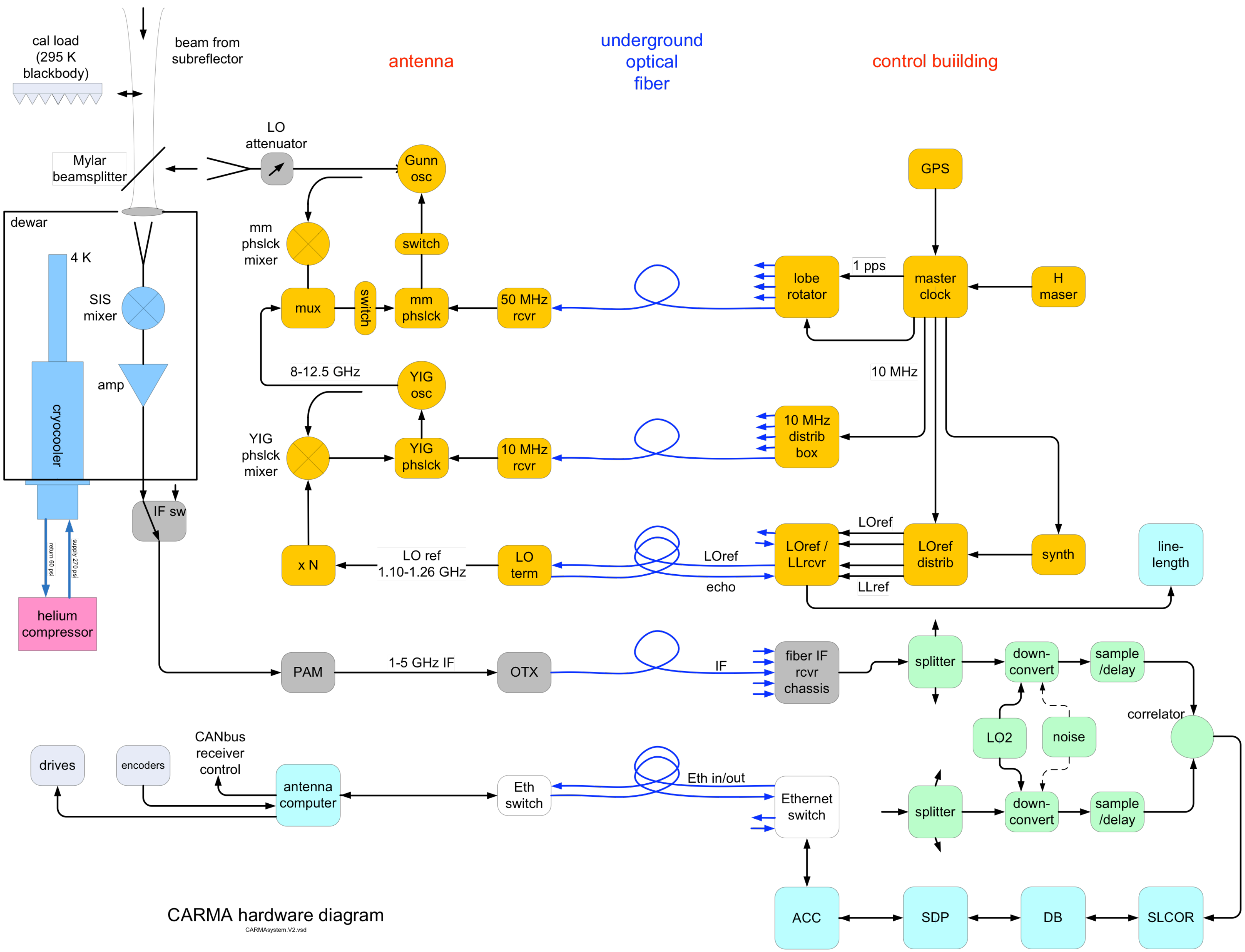
fluctuations in Tsys

- remember that T_{sys} is the AVERAGE noise power
- fluctuations in Tsys:

$$\Delta T = \frac{Tsys}{\sqrt{\Delta \upsilon \, \tau}}$$

- so fluctuations are greater on ambient load or the Sun than on cold sky





CARMA hardware diagram

CARMAsystem.V2.vsd