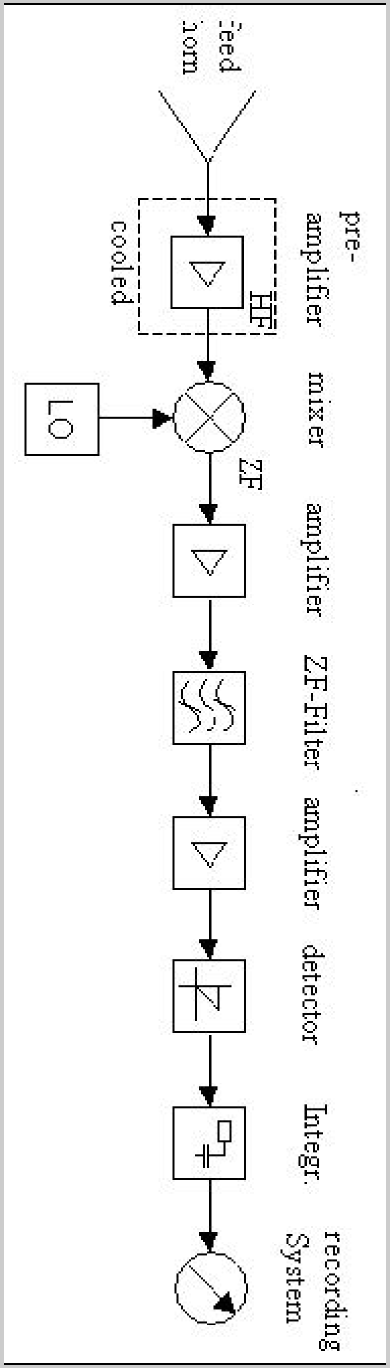
Receivers in Radio Astronomy



Receivers in Radio Astronomy

The Antenna

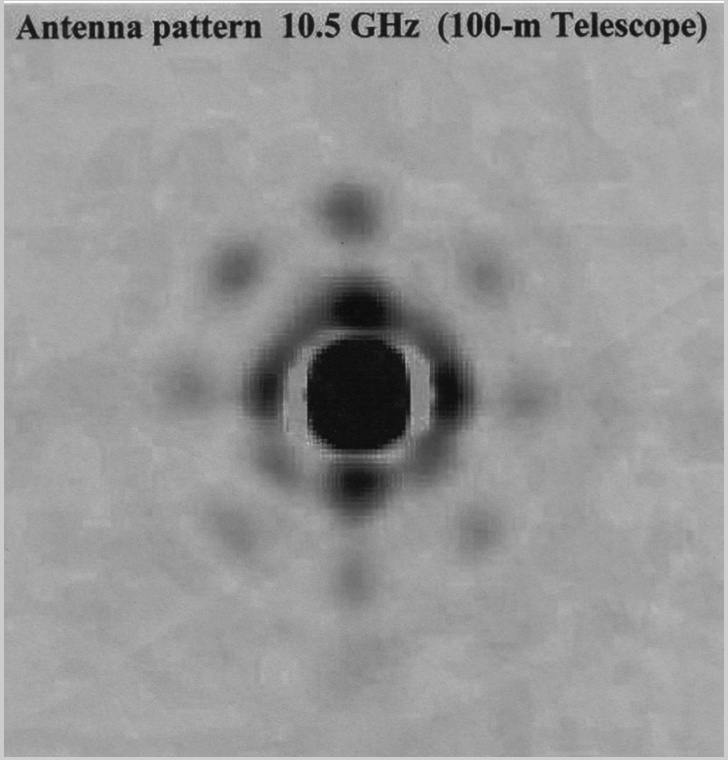
First element: Antenna

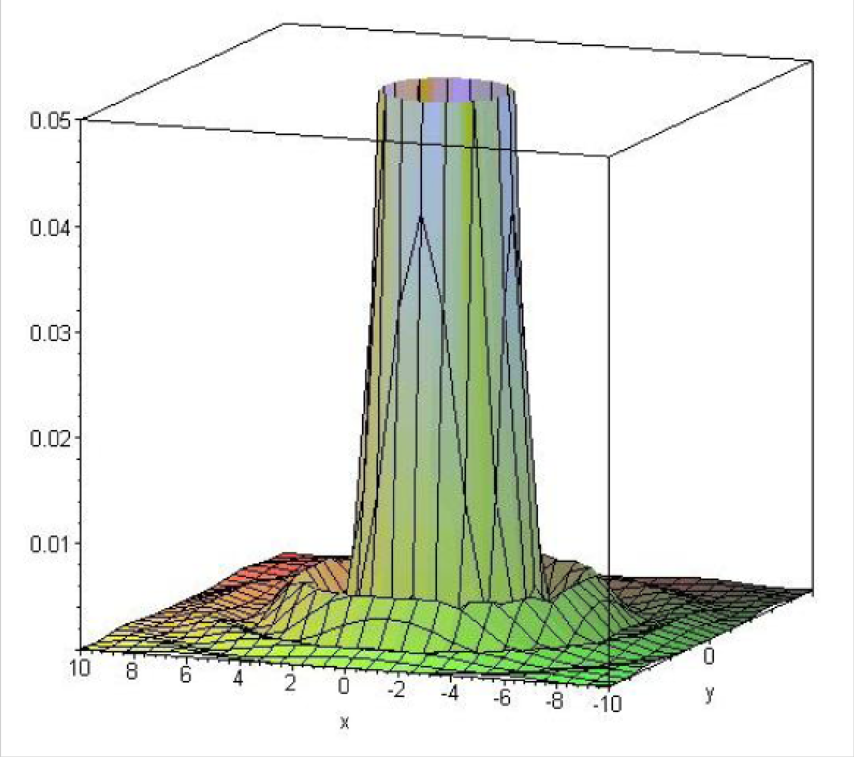
-collects radiation from the sky
-can receive and transmit
-defines observation direction

What are an antenna's properties?

The Antenna

Sample antenna diagram





Antenna pattern: Fourier transform of E-field in aperture plane

The Antenna

FWHM of primary beam:

$$F(\xi) = \left[\frac{2 \cdot J_1(\pi \cdot \xi \cdot D_\lambda)}{\pi \cdot \xi \cdot D_\lambda}\right]^2$$

$$HPBW \quad = \quad 1.02 \cdot \frac{\lambda}{D} = 58^\circ\!.4 \cdot \frac{\lambda}{D} \text{ rad}$$

FWHM when aperture is tapered

$$HPBW = 1.22 \cdot \frac{\lambda}{D} \text{ rad} = 70^\circ \cdot \frac{\lambda}{\mathrm{D}}$$

Radio: λ~1cm, D~25m, HPBW = 70° x 0.01m / 25m = 0.028° =1'40''
Optical: λ~500nm, D~4m, HPBW = 58°.4 x 500nm/4m = 26mas

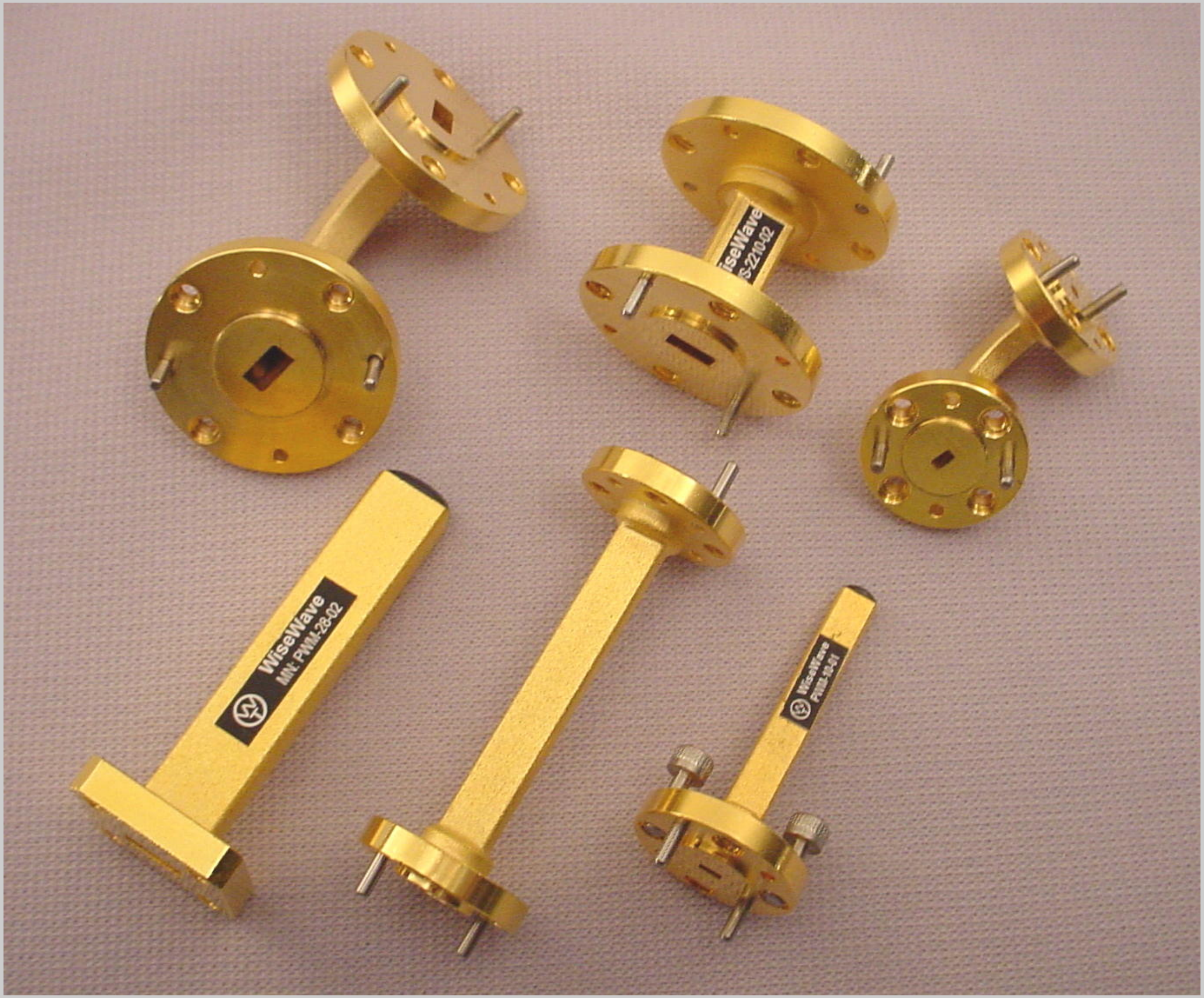
The feed

-Feed horns convert freely propagating waves into waveguide waves

-The feed's shape defines the taper and so influences the antenna pattern

The feed

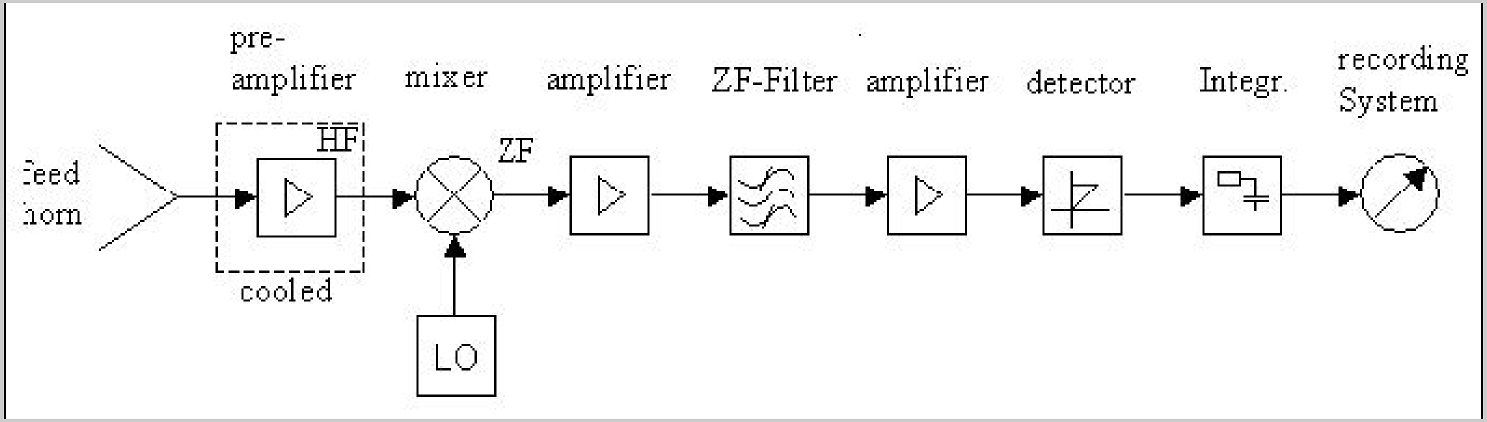
Waveguides



The LNA and mixers

Amplifiers need to amplify signals by $10^8 \ldots 10^9$

-the smallest leakage from output into input would cause strong feedbacks



Solution: decouple input and output by converting to low frequencies -> mixing

The LNA and mixers

The LNA (Low-noise amplifier) is the first active component in the receiver

-contributes ~90% of the noise and commonly is cooled with LHe to ~15K

-broad-band

The LNA and mixers

The so-called heterodyne principle:

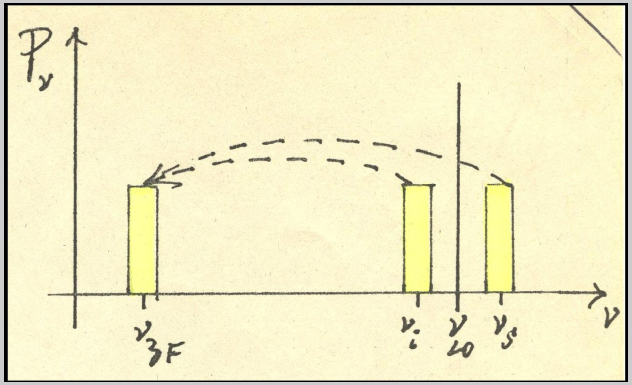
-inject sky signal and a locally generated signal at f_{LO} into a diode with a square law I-U characteristic

-the output contains signals from f_{LO}-f_{sky} and f_{LO}+f_{sky}

-all further processing is done at the intermediate frequency, or IF, at $|f_{LO}-f_{sky}|$

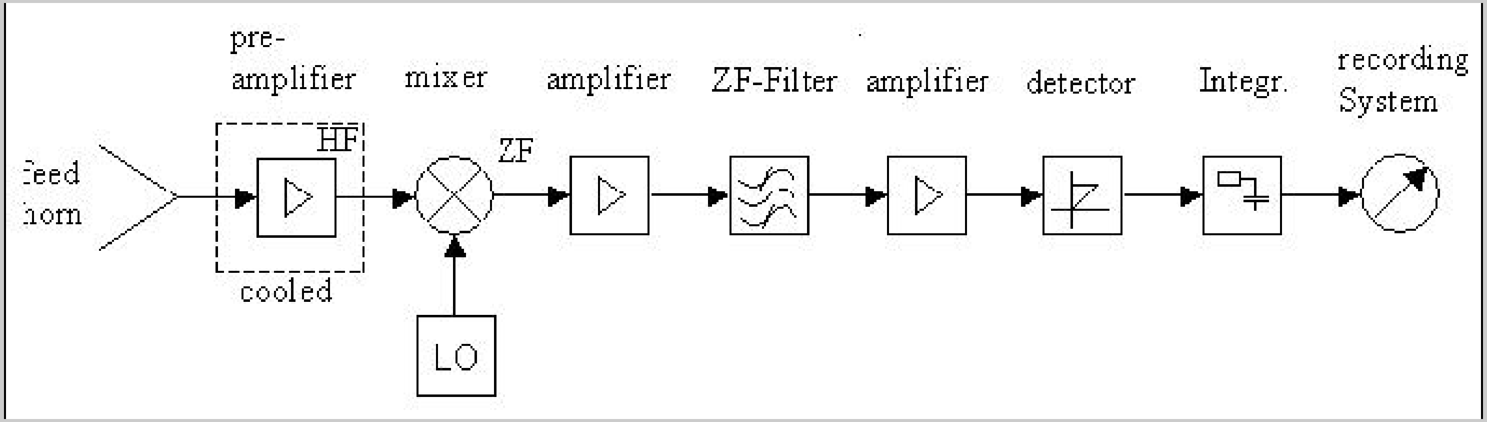
-further advantages:

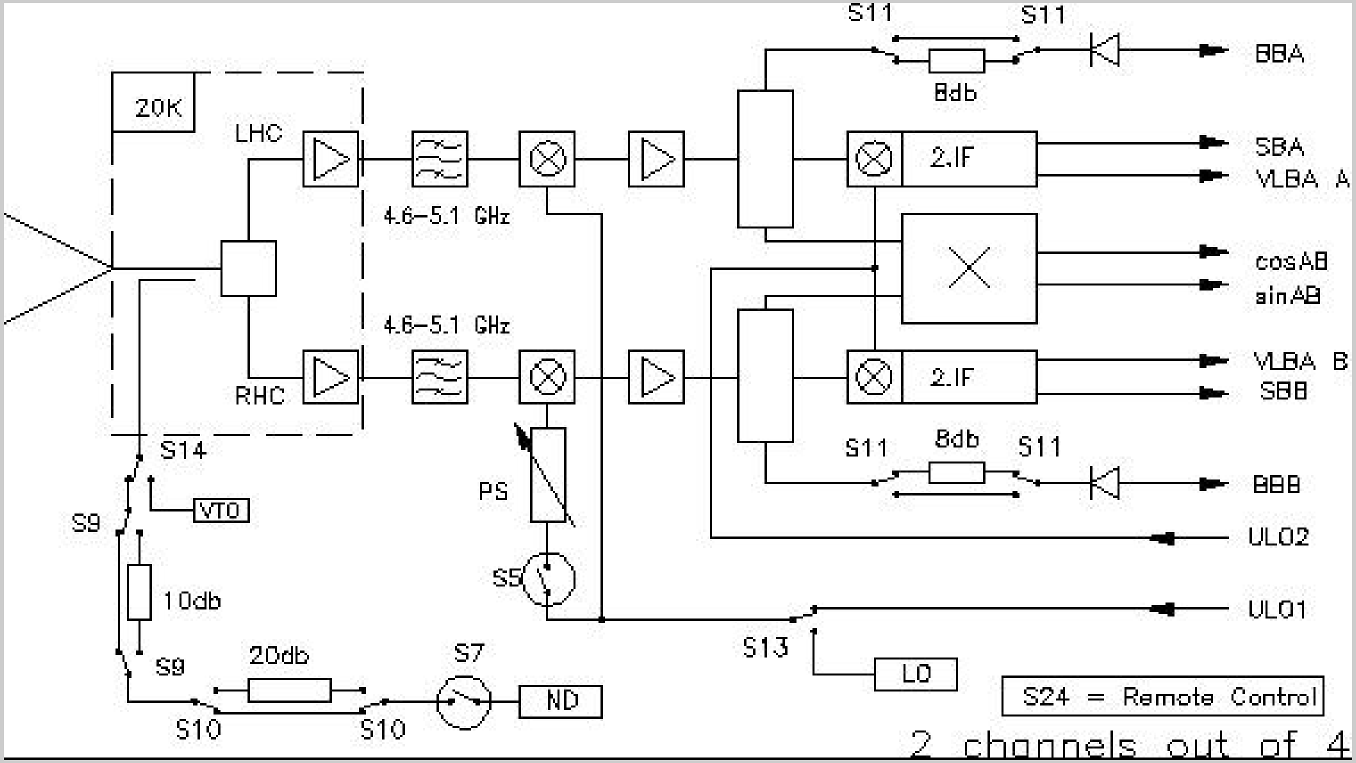
- easy to get signal to control room
- easy to build
- cheap
- tune receiver by changing f_{LO}
- -> use one backend for all frequencies!



The backend

The rest of the system is “relatively simple” HF technology





Sensitivity

Monochromatic power intercepted by antenna:

$P_\nu = A_{eff} \times S_\nu$

Receivers are polarization-sensitive, and have a finite bandwidth, hence

$P = 0.5 \times A_{eff} \times S_\nu \times \Delta\nu$

For example, $A_{eff} = 0.6 \times A = 0.5 \times 12.5^2 m^2 \times \pi = 294 m^2$

$S_\nu \;= 1\ \text{Jy} = 10^{-26}\ \text{W m}^{-2}\ \text{Hz}^{-1}$

$\Delta\nu = 50\ \text{MHz}$

$\rightarrow P \;= 0.5 \times 294\ m^2 \times 10^{-26}\ \text{W m}^{-2}\ \text{Hz}^{-1} \times 50\ \text{MHz}$

$= 7.35 \times 10^{-17}\ \text{W}$

Radio astronomy signals are extremely weak!

Sensitivity

Nyquist noise: $P = k_B T \Delta\nu$

Antenna temperature:

$P = 0.5 \times A_{eff} \times S_\nu \times \Delta\nu = k_B T_{ant} \Delta\nu$

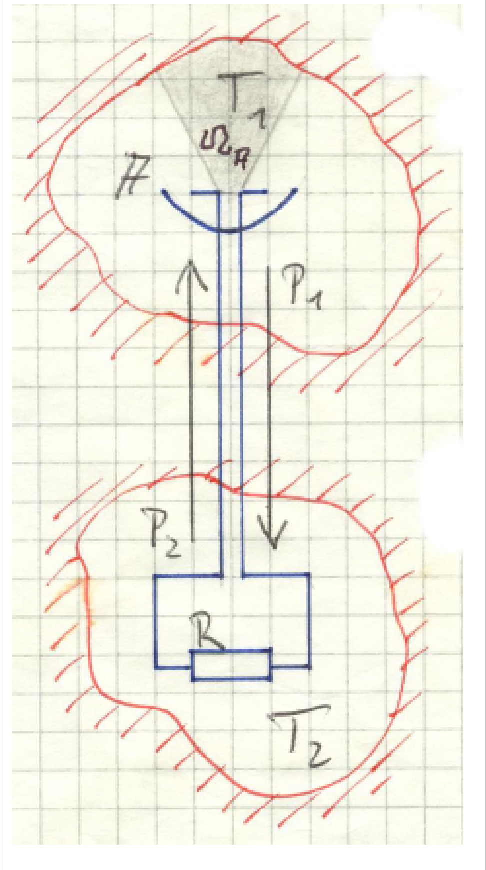
-> $S_\nu = 2k_B T_{ant} / A_{eff}$

Factor $2k_B / A_{eff}$ has units of Jy/K

Typical system noise is $T_{sys} = 50K$, hence

$SEFD = 2k_B T_{sys} / A_{eff} = 470$ Jy

SEFD = System Equivalent Flux Density



Sensitivity

Radiometer equation:

$\Delta T = \text{const.} \times T_{tot}/\text{sqrt}(\Delta\nu\Delta\tau)$

$T_{tot} = T_{sys} + T_{atm} + T_{grnd} + T_b$

Typical contributions are

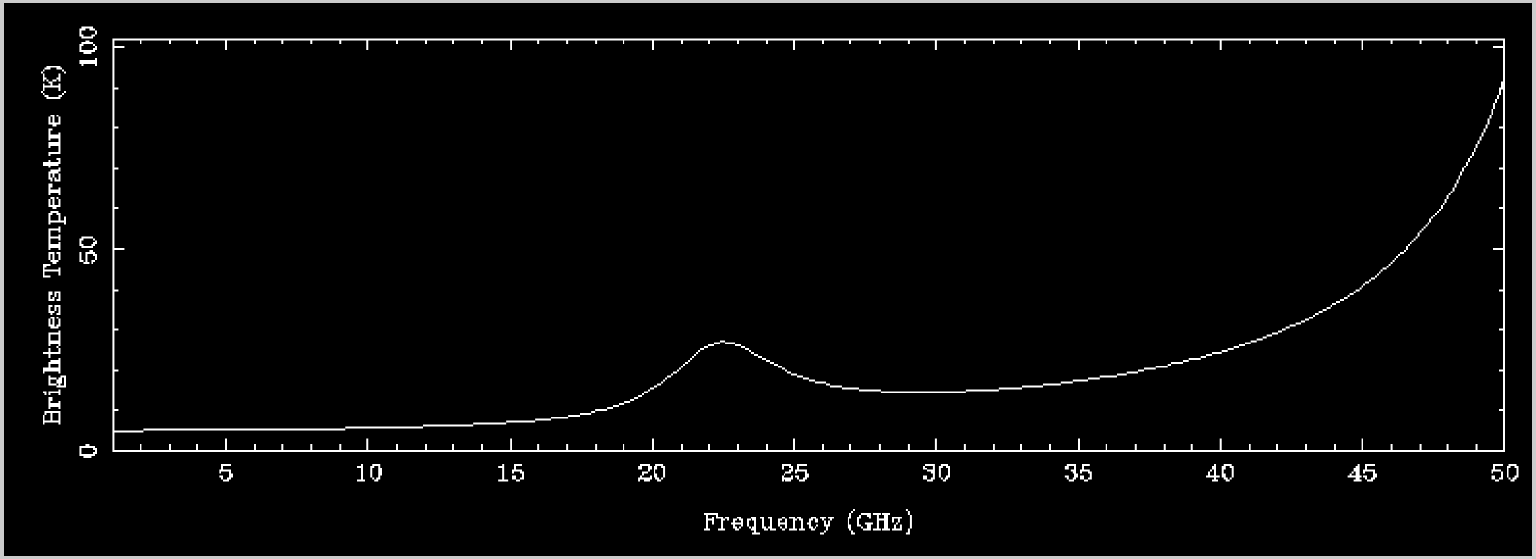
T_{sys} = 20K ... 50K

T_{atm} = 2K (2GHz) ... 50K (50 GHz)

(Isn't T_{atm} = 300K?)

T_{grnd} = 10K ... 25K

$T_b = 10^{-3}$ K ... 1000 K



T_{atm} strong function of elevation

Sensitivity

Radiometer equation:

ΔT = const. x $T_{tot}/\mathrm{sqrt}(\Delta\nu\Delta\tau)$

$\Delta\nu$ = 1 MHz ... 512 MHz, and 2 GHz ... 4 GHz not far away

$\Delta\tau$ = typically tens of minutes to hours per source

So for SEFD=500 Jy and S=1 Jy, SNR=1/500

But for $\Delta\nu$=50 MHz and $\Delta\tau$=1 min, SNR= 1/500 x sqrt(50 MHz * 60s)
= 109

Sensitivity

Sensitivity can be increased by increasing $\Delta\tau$, $\Delta\nu$, and A_{eff}

However:

- $\Delta\tau$: not always practical, can quickly become ridiculously large
- $\Delta\nu$: technically limited, doesn't help in spectral line work
- A_{eff}: not possible after telescope has been built
  - meachanical and financial limits
  - (cost of telescope scales as $D^{2.7}$)

Observations can be dynamic-range-limited, rather than sensitivity-limited.