Receivers in Radio Astronomy
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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:

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

\[H \text{P}B\text{W} = 1.02 \cdot \frac{\lambda}{D} = 58.4 \cdot \frac{\lambda}{D} \text{ rad}\]

FWHM when aperture is tapered

\[H \text{P}B\text{W} = 1.22 \cdot \frac{\lambda}{D} \text{ rad} = 70^\circ \cdot \frac{\lambda}{D}\]

Radio: \(\lambda \sim 1\text{cm}, D \sim 25\text{m}, HPBW = 70^\circ \times 0.01\text{m} / 25\text{m} = 0.028^\circ = 1'40''\)

Optical: \(\lambda \sim 500\text{nm}, D \sim 4\text{m}, HPBW = 58^\circ.4 \times 500\text{nm}/4\text{m} = 26\text{mas}\)
The 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
Amplifiers need to amplify signals by $10^8...10^9$

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

Solution: decouple input and output by converting to low frequencies -> mixing
The LNA (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
Monochromatic power intercepted by antenna:
\[ P_v = A_{\text{eff}} \times S_v \]
Receivers are polarization-sensitive, and have a finite bandwidth, hence
\[ P = 0.5 \times A_{\text{eff}} \times S_v \times \Delta \nu \]

For example, \( A_{\text{eff}} = 0.6 \times A = 0.5 \times 12.5^2 \text{m}^2 \times \pi = 294 \text{m}^2 \)
\[ S_v = 1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} \]
\[ \Delta \nu = 50 \text{ MHz} \]
\[ -> P = 0.5 \times 294 \text{ m}^2 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} \times 50 \text{ MHz} \]
\[ = 7.35 \times 10^{-17} \text{ W} \]

Radio astronomy signals are extremely weak!
Nyquist noise: \[ P = k_B T \Delta v \]

Antenna temperature:

\[ P = 0.5 \times A_{\text{eff}} \times S_v \times \Delta v = k_B T_{\text{ant}} \Delta v \]

\[ \Rightarrow S_v = 2k_B T_{\text{ant}} / A_{\text{eff}} \]

Factor \( 2k_B / A_{\text{eff}} \) has units of Jy/K

Typical system noise is \( T_{\text{sys}} = 50 \text{K} \), hence

\[ \text{SEFD} = 2k_B T_{\text{sys}} / A_{\text{eff}} = 470 \text{ Jy} \]

SEFD = System Equivalent Flux Density
Sensitivity

Radiometer equation:

\[ \Delta T = \text{const.} \times \frac{T_{\text{tot}}}{\sqrt{\Delta \nu \Delta \tau}} \]

\[ T_{\text{tot}} = T_{\text{sys}} + T_{\text{atm}} + T_{\text{grnd}} + T_{b} \]

Typical contributions are

\[ T_{\text{sys}} = 20K \ldots 50K \]

\[ T_{\text{atm}} = 2K \ (2\text{GHz}) \ldots 50K \ (50 \text{ GHz}) \]

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

\[ T_{\text{grnd}} = 10K \ldots 25K \]

\[ T_{b} = 10^{-3} \text{ K} \ldots 1000 \text{ K} \]

\( T_{\text{atm}} \) strong function of elevation
Sensitivity

Radiometer equation:

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

$$\Delta \nu = 1 \text{ MHz} \ldots 512 \text{ MHz}, \text{ and } 2 \text{ GHz} \ldots 4 \text{ GHz} \text{ not far away}$$

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

So for $\text{SEFD}=500 \text{ Jy}$ and $S=1 \text{ Jy}$, $\text{SNR}=1/500$

But for $\Delta \nu=50 \text{ MHz}$ and $\Delta \tau=1 \text{ min}$, $\text{SNR}= \frac{1}{500} \times \sqrt{50 \text{ MHz} \times 60\text{s}}$

$$= 109$$
Sensitivity can be increased by increasing $\Delta \tau$, $\Delta \nu$, and $A_{\text{eff}}$

However:

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

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