Single-dish radio telescopes

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APEX

Single-dish radio telescopes

Medicina

Nobeyama

Nobeyama

Radio telescopes (single dish)

- https://en.wikipedia.org/wiki/List_of_radio_telescopes

- IRAM (Spain) 30 m: https://iram-institute.org/science-portal/
- Greenbank (USA) 100 m: https://greenbankobservatory.org/
- Onsala Space Observatory (Sweden) 20 m: https://www.chalmers.se/en/infrastructure/oso/
- Parkes (Australia) 64 m: https://www.parkes.atnf.csiro.au/
- Effelsberg (Germany) 100 m:
- https://www.mpifr-bonn.mpg.de/en/effelsberg
- APEX (Chile) 12 m: http://www.apex-telescope.org/ns/
- Nobeyama (Japan) 45 m: https://www.nro.nao.ac.jp/en/
- Medicina (Italy) 32 m: http://www.med.ira.inaf.it/

Arrays of radio telescopes

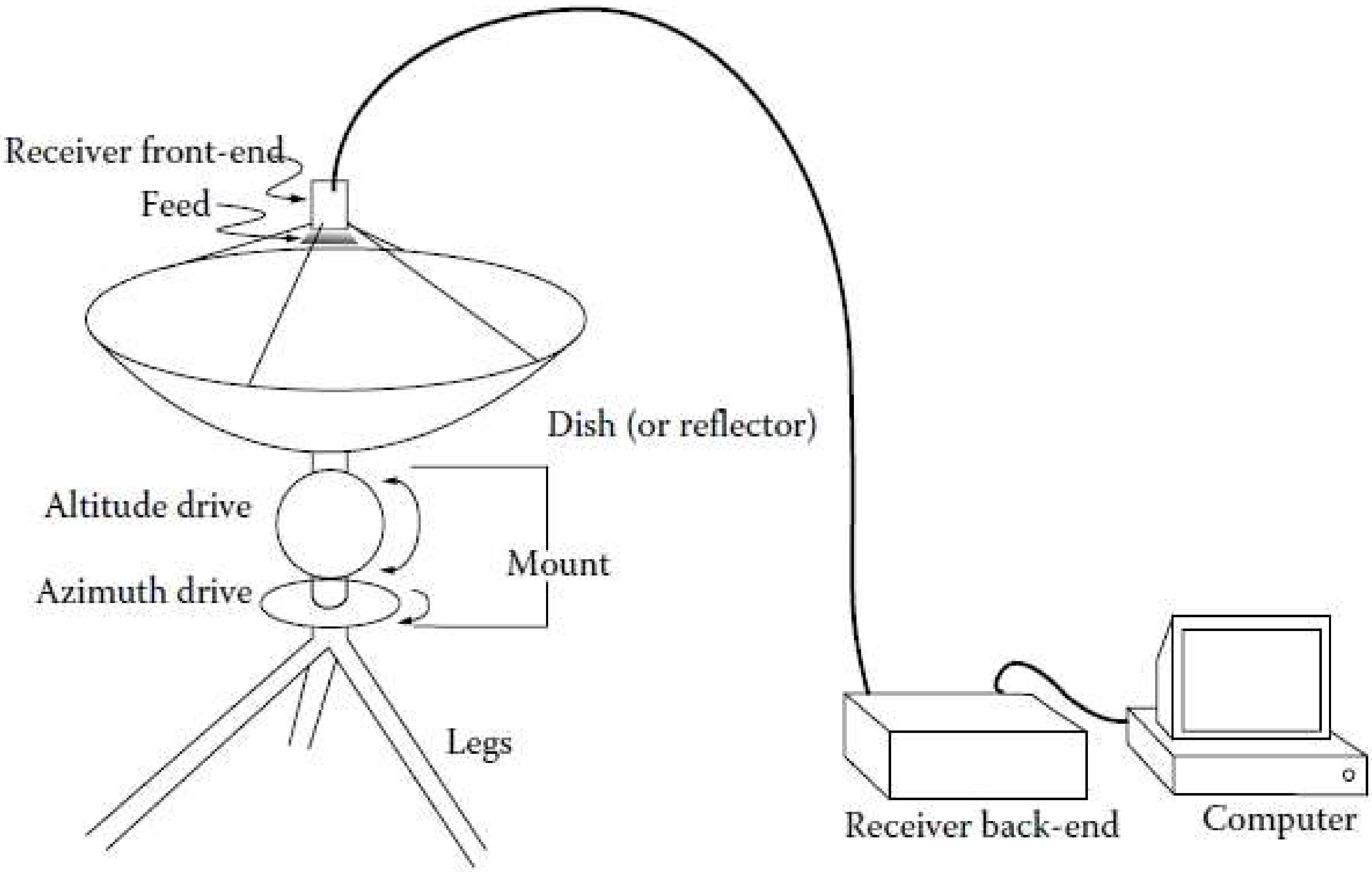
Radio Astronomy

- History.
- Transparency of the atmosphere.
- Fundamental discoveries:
  - Spiral structure of the Milky Way: detection of the interstellar gas clouds
  - Pulsars
  - Cosmic microwave background
- Typical radio sources:
  - In our Galaxy: supernova remnants, interstellar clouds, HII regions.
  - Extragalactic sources: active galaxies, quasars.
  - In the solar system: Jupiter, Sun.

Radio Astronomy

- Low frequency, $h\nu << kT$, Rayleigh-Jeans.
- Electromagnetic waves (***E***, ***B***).
- Power $\propto E^2$.
- Specific intensity (brightness), $I_\nu \propto E_0^2$.
- Flux density, F_ν or S_ν .
- Antenna: reciprocity theorem: The properties of an antenna are the same, whether it is used as a receiving element or as a transmitting element.

Radio Telescope



Radio telescope reflectors, Antennas, Feeds

- Radio telescope reflector:
  - Primary parabolic reflector: collects and concentrates the light into the prime focus.
- Antenna:
  - Couples free EM waves in space to confined waves in transmission lines.
- Feed (horn):
  - Device that couples the radiation concentrated by the reflector into a transmission line.

Primary reflector: two functions

1. Collects the radiation from astronomical sources. The amount depends on the telescope's effective area (A_{eff}), related to the geometric area.

- The power of the radiation collected from a source with flux density F_ν is: $P = F_\nu A_{eff} \Delta\nu$

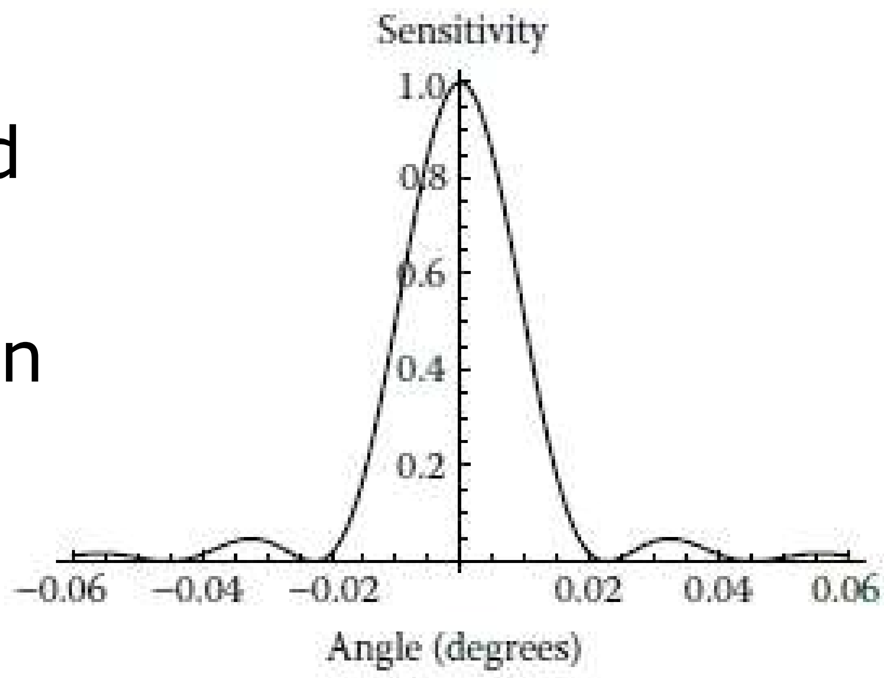
  $\Delta\nu$ = bandwidth or range of frequencies detected.

2. Provides directivity to differentiate the emission from objects at different positions on the sky.

- Determines the angular resolution due to diffraction

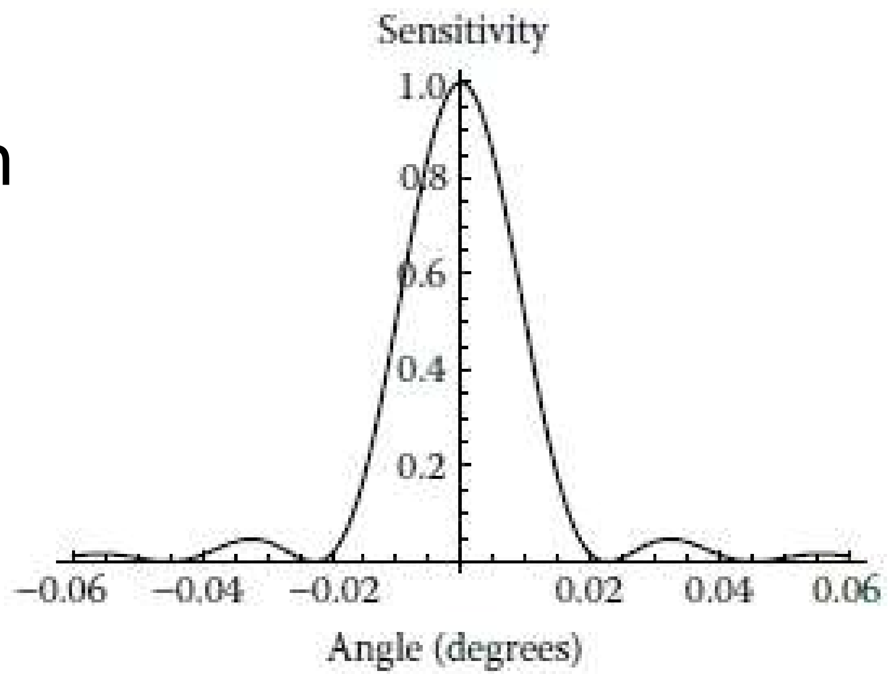
Beam pattern

- Measure of the sensitivity of the telescope to incoming radiation as a function of angle on the sky. (similar to the “point spread function”)
- Diffraction at the edges of the aperture determines the appearance of a pattern of constructive and destructive interference.
- For an uniformly illuminated circular aperture, the total collected power is zero when the source is 1.22 (λ/D) radians from the central axis.

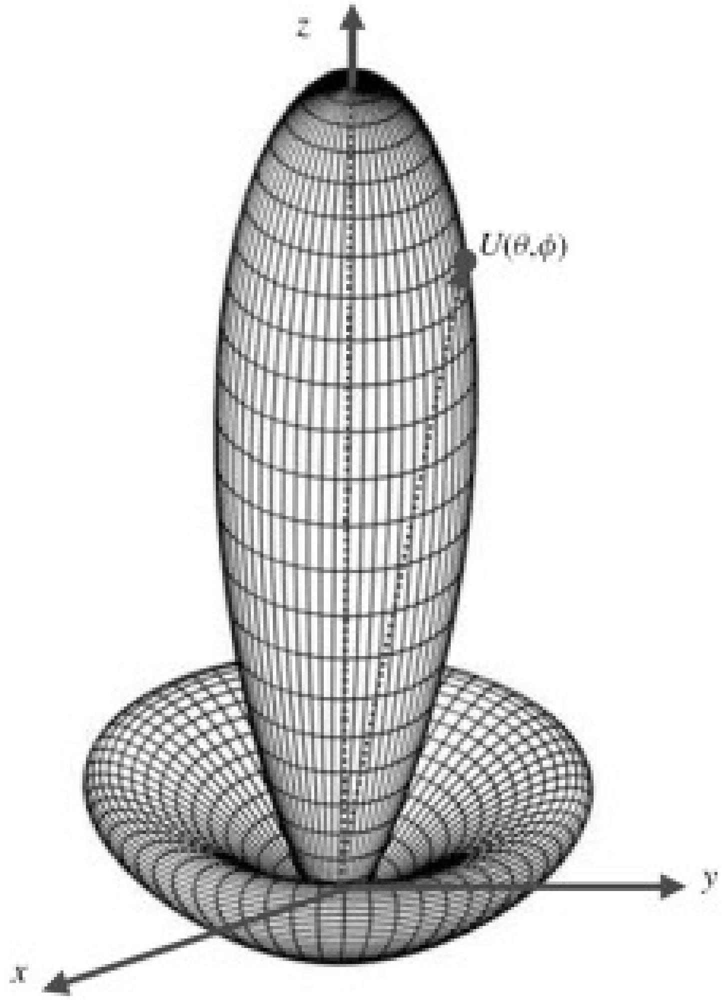


Beam pattern

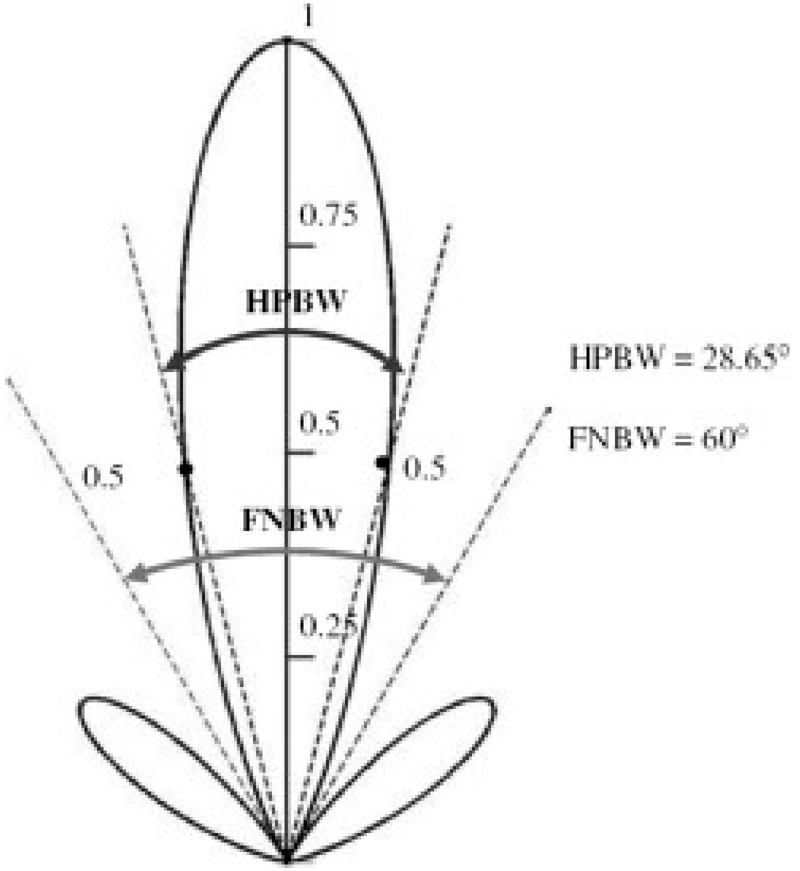
- *Main beam*: central peak.
- *Sidelobes*: after reaching zero, there are other positions where there is partial constructive interference. May reach 1% of the peak value.
- FWHM of the main beam = angular resolution θ_{FWHM}
- It is not 1.22 (λ/D).
- Depends on the illumination pattern (antenna design).
- θ_{FWHM} = 1.02 (λ/D)
- θ_{FWHM} = 1.15 (λ/D) (optimum illumination)



Beam pattern



(a) Three dimensional



(b) Two-dimensional

Feed

- At the focus, a feed sends the waves to the receiver.
- Transmission line (wave guide, coaxial cable).
- Minimum size opening ~ λ.
- Diffraction determines its own beam pattern → the sensitivity is not uniform for radiation from different parts of the dish.
- Equivalently, the feed horn does not illuminate uniformly the dish.
- The beam pattern of the feed determines the *illumination pattern* of the primary reflector.

Feed

- If the illumination pattern extends beyond the dish, there is loss of radiation, called *spillover*.
- *Spillover* is the illumination of the feed beyond the reflector.
- The illumination pattern affects:
  - The angular resolution
  - The sensitivity of the side lobes
  - The effective collecting area
- The best compromise that maximizes the effective collecting area and reduces *spillover* results also in good compromise for the resolution and low sidelobe level.

Feed

- The best compromise that maximizes the effective collecting area and reduces *spillover* results also in good compromise for the resolution and low sidelobe level.
- It results in $\theta_{FWHM} = 1.15\ (\lambda/D)$

Effective area

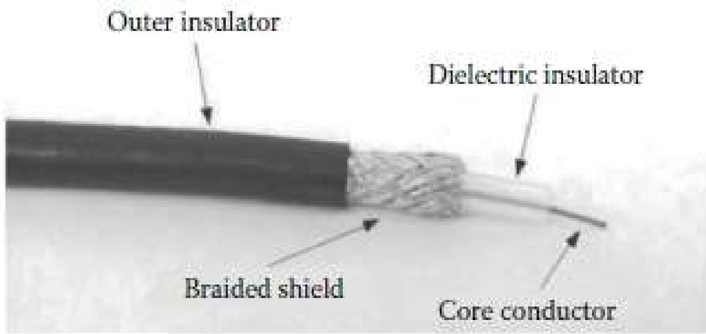
- The effective area is a crucial parameter that determines many properties of radio telescope system.
- $\max(A_{eff}) = A_{physical}$.
- Every process that leads to loss of radiation reduces A_{eff}:
    - Blockage by the feed horn or the secondary reflector
    - Illumination pattern
    - *Error pattern* (deviations of the dish surface from a perfect parabola originates a large beam called *error pattern*).

Heterodyne receivers

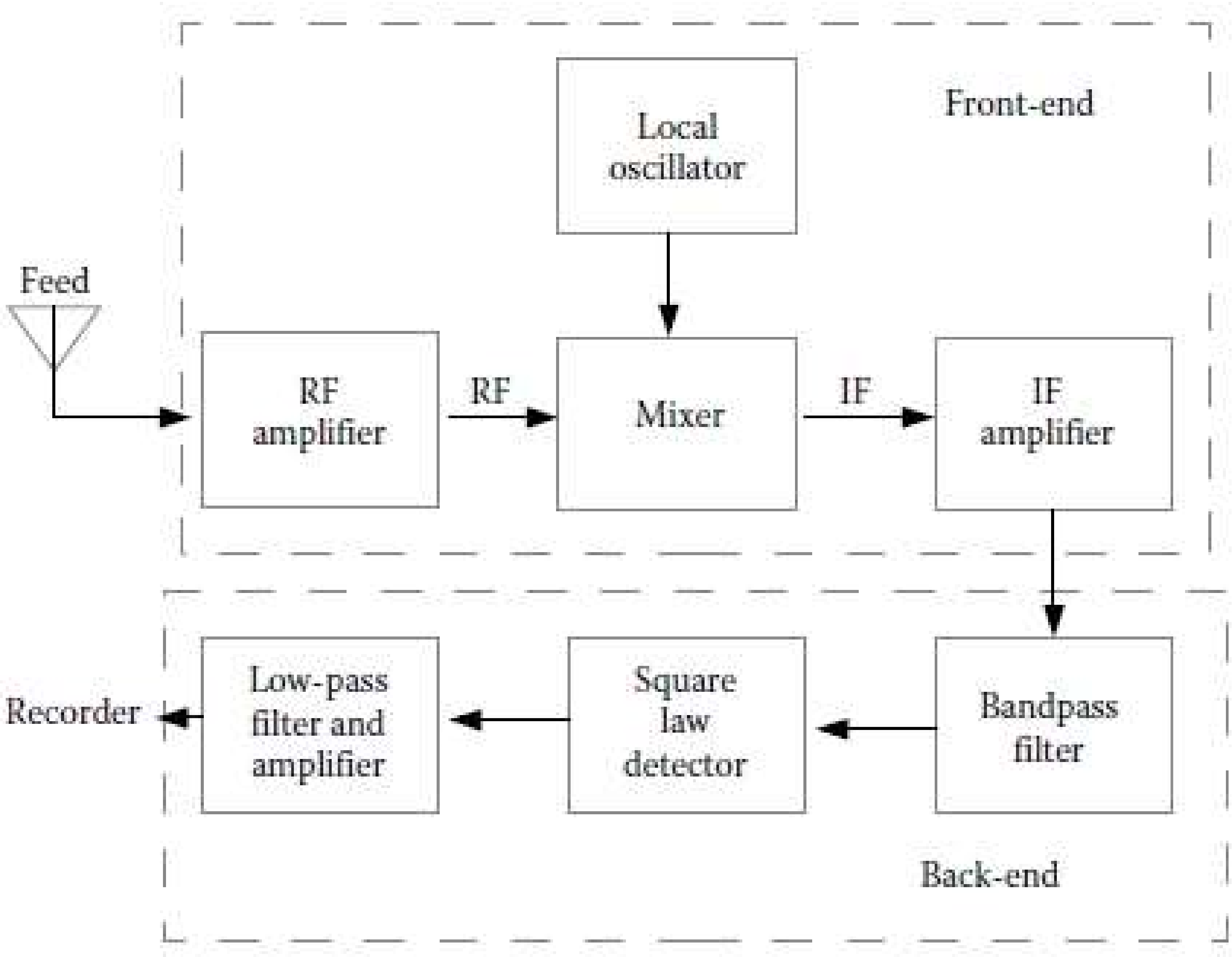
- It is difficult to amplify and analyze high-frequency signals (GHz).
- *Heterodyning* or *Mixing* is the process of converting high-frequency signals to low-frequency.

Heterodyne receivers

- A receiver:
  - defines the frequency range, or passband
  - produces a signal proportional to the collected power
- *Front-end* (near the focus) and *back-end* (away from the telescope)
- Transmission lines:
  - Transmit RF waves from the feed to the front-end receiver components and then to the back-end receiver components.



Heterodyne receivers



Front-end receiver components

1. *RF Amplifier*:
   - Amplifier gain: $G = \frac{P_{out}}{P_{in}}$ $G(\mathrm{dB}) = 10 \log_{10} G$
2. *Mixer*, containing the *local oscillator* (LO).
   - A device with a non-linear I-V characteristic curve.
     Simplest case: $I = \alpha V^2$.
   - Transforms the radio frequency (RF) signal into a intermediate frequency (IF) signal, by mixing a local input signal.
   - Lowers the frequency keeping all the information in the original RF signal.
   - Examples: Schottky diode, SIS, SIN (Superconductor-Insulator-Normal metal).

Mixer

- Sky frequency RF signal, ω_{RF} ou ω_S: $V_S=V_{S0}\cos(\omega_S t+\theta_S)$
- Local oscillator frequency: $V_L=V_{L0}\cos(\omega_L t+\theta_L)$
- $I=\alpha V^2= \alpha(V_S+V_L)^2$
- $I/\alpha = V_{S0}^2 \cos^2(\omega_S t+\theta_S) + V_{L0}^2 \cos^2(\omega_L t+\theta_L) +$
  $2V_{S0}V_{L0}\cos(\omega_S t+\theta_S)\cos(\omega_L t+\theta_L) =$

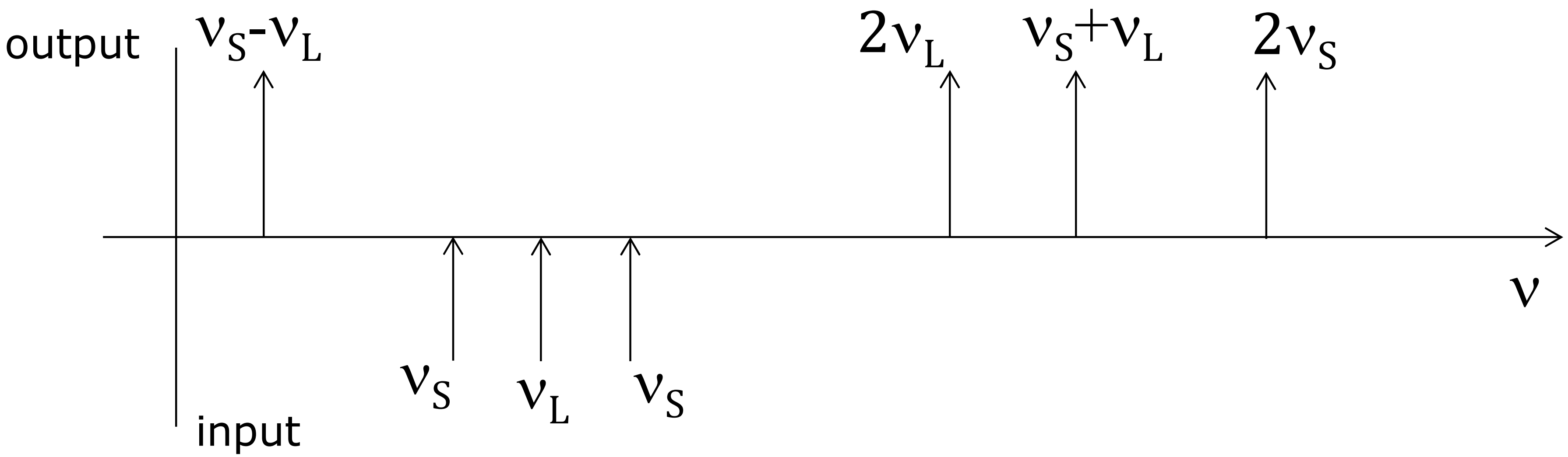
  = DC component + 2nd harmonic of V_S + 2nd harmonic of V_L

$+ V_{S0}V_{L0}\cos[(\omega_S+\omega_L)t +(\theta_S+\theta_L)] + V_{S0}V_{L0}\cos[(\omega_S-\omega_L)t +(\theta_S-\theta_L)]$

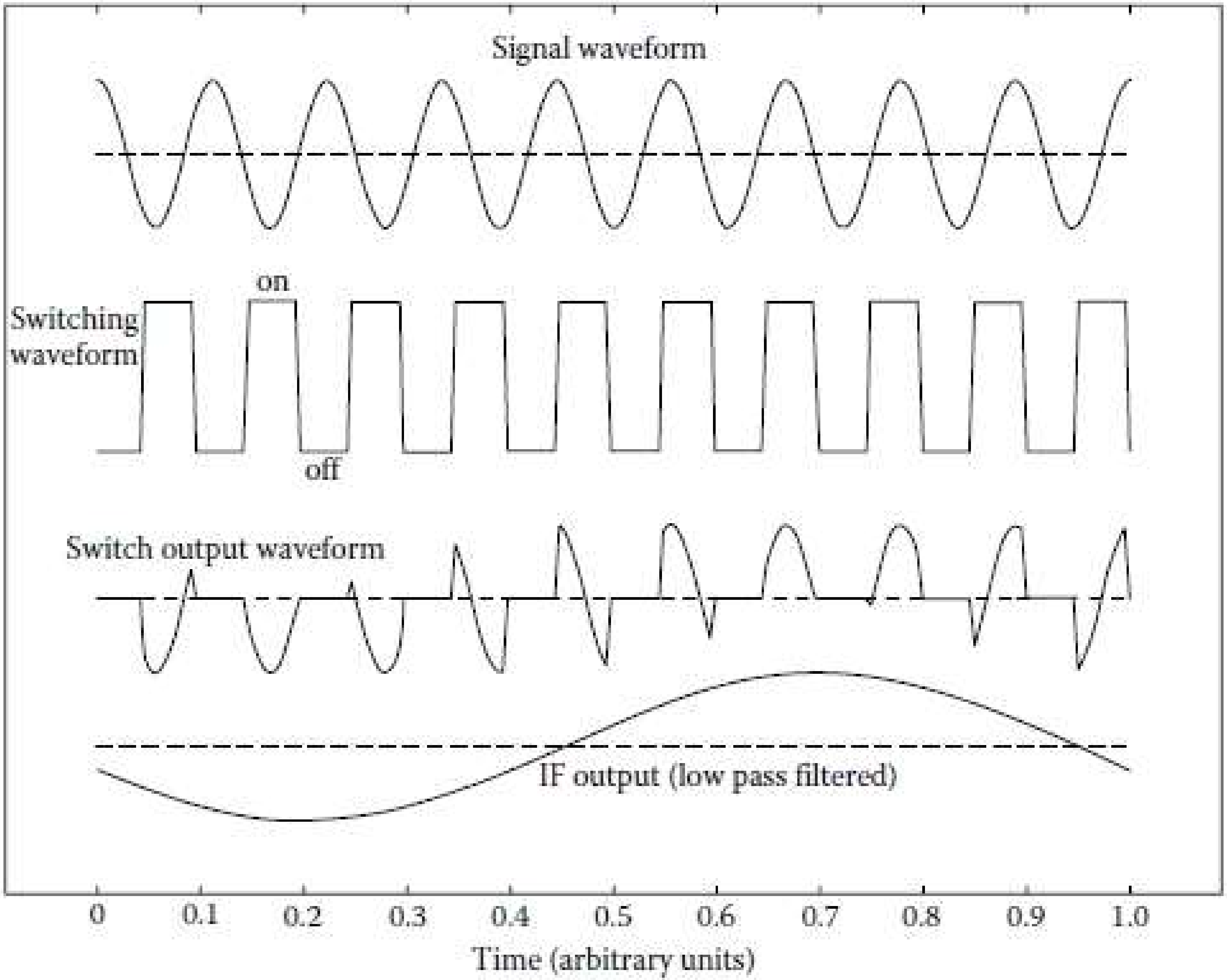
- Filtering out all components except the last one, we get the intermediate frequency IF: $\nu_{IF}=\nu_S- \nu_L$
- The output is linear (proportional to V_{S0}).
- Phase is conserved: $\theta_S \rightarrow \theta_S+\Delta\theta_S$ is replicated in the output.

Mixer

- Double-sideband mixer: for a given IF, there are two sky RF that will be mixed to that same IF (double-sideband mixers, with the upper sideband and the lower sideband).
- $\nu_S = \nu_{LO} \pm \nu_{IF}$
- Single-sideband mixers eliminate one band.
- We end up with a much lower frequency signal, keeping all the original information.



Mixing



Signal waveform
on
Switching waveform
off
Switch output waveform
IF output (low pass filtered)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Time (arbitrary units)

Front-end receiver components

- *IF Amplifier*:
  - Differently designed amplifier, for lower frequencies.
- Need different receivers (and feeds) for different frequencies, installed at the telescope.

Back-end receiver components

- The output of the front-end is still an EM wave and needs to be detected and registered.
- *Bandpass filter:* defines the frequency range that will be detected.
- *Square-law detector*: detects the power in the wave.
- Usually a diode (produces a current proportional to the square of the electric field:
  - $V \propto E^2 \propto (E_0 \cos(\omega t))^2 \propto E_0^2 \cos^2(\omega t)$
  - $V \propto E_0^2 [1+\cos(2\omega t)]$
  - Using a low-pass filter, $V \propto E_0^2 \propto P$, ou $V=\alpha P$
  - α is the responsivity of the detector, conversion of power in the radiation into voltage.

Back-end receiver components

- Minimum power required for a detector is $\sim 10^{-6}$ W >> power from any astronomical source. $\Rightarrow$ Need amplification of 90 dB (a factor of 10^9!).
- Typical value of α ~100 V W^{-1} $\Rightarrow$ output V = 0.1 mV
- This is a small value $\Rightarrow$ DC amplifier to increase the voltage before being digitized by an A/D converter and registered.

High frequency heterodyne receivers

- At high-frequencies (RF>~300 GHz), the amplifiers are very noisy.
- Requires first mixing RF to get IF and then amplifying the signal. Thus, the first device is the mixer (not the RF amplifier).

Bolometers

- Broadband device for high-frequencies used for continuum emission (not spectral lines).
- Thermometer for radiation.
- Transforms radiation on heat and measures the (tiny) increase in temperature.
- Incoherent detector: detects only the energy, not the phase.
- Cannot be used for interferometry.
- At high RF, the bolometers are small $\Rightarrow$ there are arrays of bolometers (up to a few thousands) at the focal plane of millimeter telescopes.

Noise, noise temperature, antenna temperature

- Each component of the receiver contributes with a signal that adds to the astronomical signal. We call this unwanted signal *noise*.
- Nyquist: A resistor introduces electrical noise with power per Hertz that depends only on the temperature: $P = k\,T\,\Delta\nu$
- The electronic power in a circuit can be written in terms of an equivalent temperature: $T_{\mathrm{equiv}} = \dfrac{P}{k\,\Delta\nu}$
- *Noise temperature* T_{noise}: signal introduced by each electronic component.
- *Antenna temperature* T_{A}: signal from the astronomical source.

Noise and amplification

- Total signal: $P = k\,\Delta\nu\, T_A + k\,\Delta\nu\, T_N = k\,\Delta\nu\,(T_A + T_N)$
- But there is amplification. Amplifier with gain *G*:
  - The astronomical power to be detected is: $P = G\,k\,\Delta\nu\, T_A$
  - The noise power is: $P_N = G\,k\,\Delta\nu\, T_N$ (*)
- Different amplifiers with gains G_1, G_2, etc.
- The noise of the 1st amplifier is also amplified:

  $P = G_1\,k\,\Delta\nu\, T_A + G_1\,k\,\Delta\nu\, T_{N1} = G_1\,k\,\Delta\nu\,(T_A + T_{N1})$
- With a second amplifier, the power noise is:

  $P_N = G_2 G_1\,k\,\Delta\nu\, T_{N1} + G_2\,k\,\Delta\nu\, T_{N2}$
- The total gain $G = G_1\,G_2$. Define a total noise temperature T_N such that (*) holds. $\Rightarrow T_N = T_{N1} + \frac{T_{N2}}{G_1}$

Noise and amplification

- For three or more amplifiers:

The total gain $G = G_1 G_2 G_3 \ldots$ and $T_N = T_{N1} + \frac{T_{N2}}{G_1} + \frac{T_{N3}}{G_1 G_2} + \ldots$

- The contribution to the noise comes mainly from the 1st amplifier.
- Need to built very low noise amplifier for the 1st component of the front-end receiver.

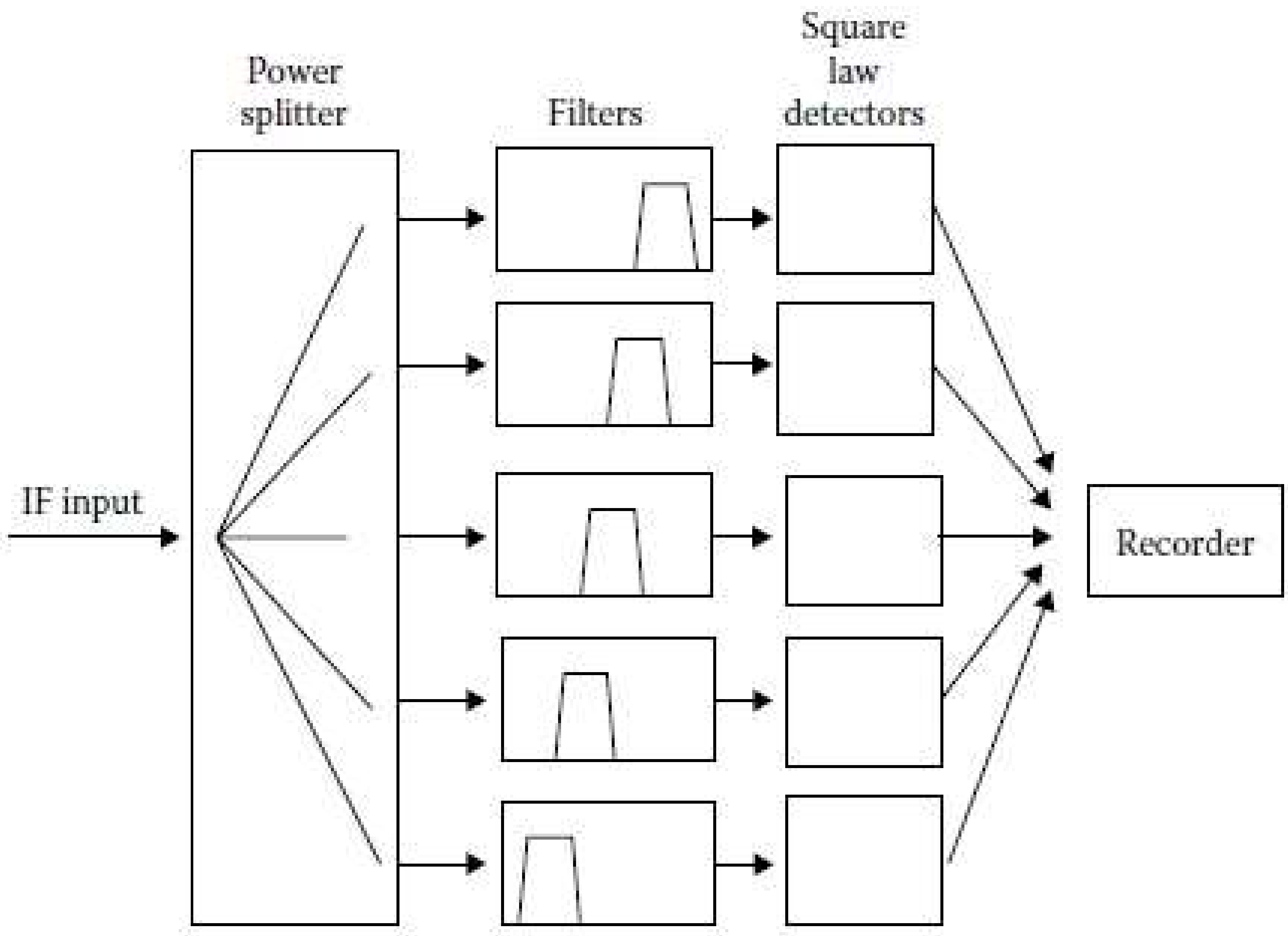
Noise and observations

- Total power reaching the detector: $P = k\,\Delta\nu\,(T_A + T_N)$
- $T_A << T_N \Rightarrow$ switched power measurements: on-source – off-source
- Uncertainty due to fluctuations in T_A and T_N, or P_A and P_N (variance σ^2 or standard deviation σ).
- The variance in the power depends on fluctuations:
  - in the number of photons: $\sigma^2 \propto n$
  - in the power of the waves: $\sigma^2 \propto E^2 \propto n^2$
- For low frequencies, $n >> 1$, $\sigma^2 \propto n + n^2 \propto n^2$
- $\sigma_P \propto n \propto P_N$
- $\sigma_P = \dfrac{P_N}{\sqrt{\Delta t \Delta \nu}}$

Spectrometers

- Instrumentally different from the optical case. Separation of wavelengths not by optical means but electronically.
- Filter bank spectrometers: a series of bandpass filters, each centered at a different frequency (IF).
- The power is split into N channels: e.g. $N_{\rm ch} = 1024$.
- Frequency resolution (bandwidth of 1 channel): $\Delta\nu_{\rm ch}$
- Spectrum bandwidth = (number of channels) x (width of 1 channel): $\Delta\nu = N_{\rm ch}\, \Delta\nu_{\rm ch}$
- For the noise in each channel, use $\Delta\nu_{\rm ch}$.

Filter bank spectrometer

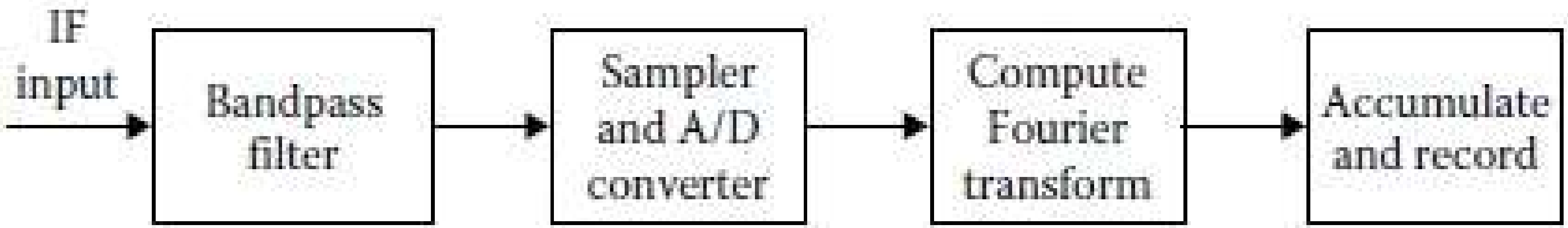


Spectrometers

- Digital spectrometers (e.g. autocorrelation spectrometer)
- We want the power spectrum $P(\nu)$.
- Wiener-Khinchin theorem: $P(\nu)$ is given by the Fourier transform of the auto-correlation function:

  $h(\tau) = \frac{1}{t_{interval}} \int a(t)\, a(t-\tau)dt$
- ACF$[E(t)]$=$\sum E(t)\, E(t-\tau)$

Digital spectrometer



Auto-correlation spectrometer