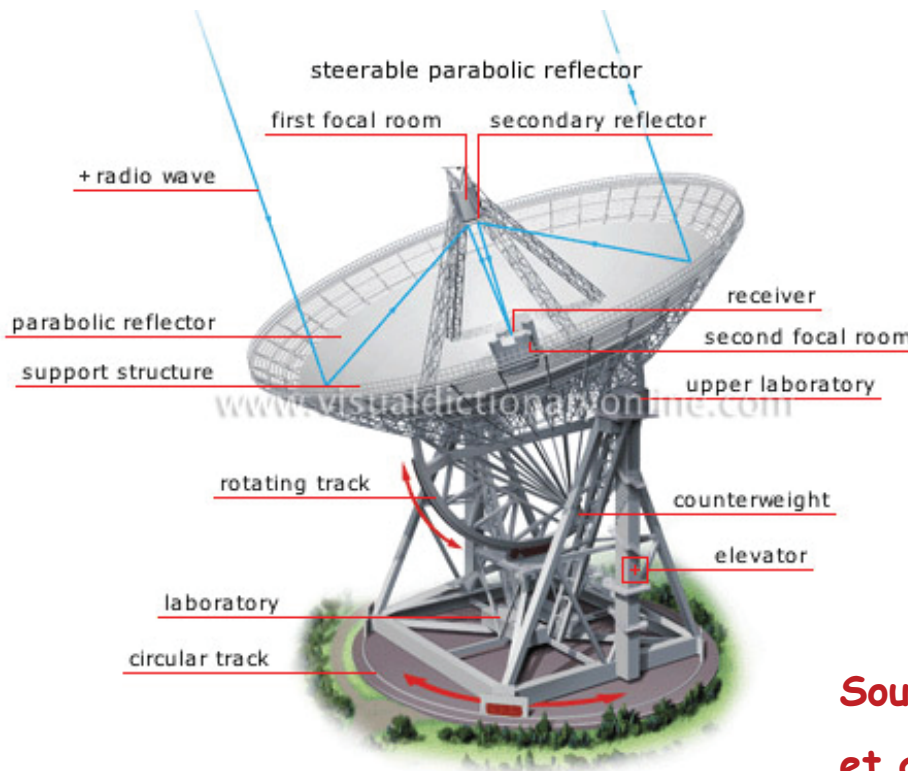


# Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

7<sup>th</sup> Lecture: 15 October 2012



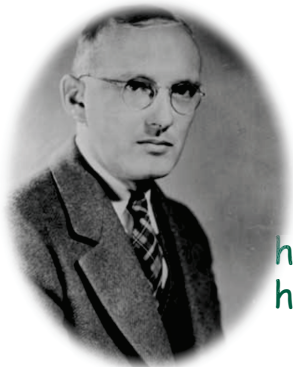
1. Introduction
2. Radio Emission
3. Observing
4. Antenna Technology
5. Receiver Technolgy
6. Back Ends
7. Calibrations

Sources: Wikipedia, Wilson et al. (2012), Rieke (2012)

# INTRODUCTION



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**Karl Guthe Jansky**  
(1905-1950)

## Brief History of Radio Astronomy

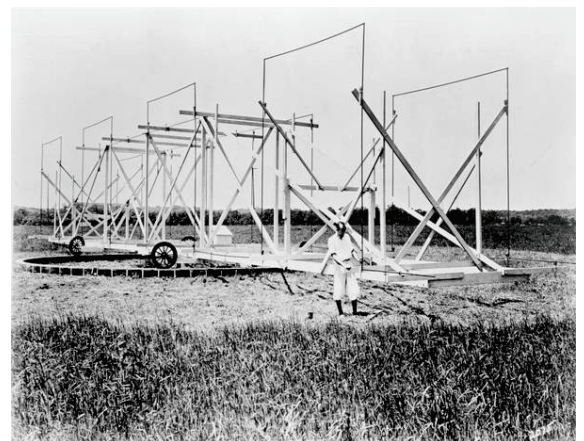
[http://en.wikipedia.org/wiki/Radio\\_telescope](http://en.wikipedia.org/wiki/Radio_telescope)  
[http://en.wikipedia.org/wiki/Radio\\_astronomy](http://en.wikipedia.org/wiki/Radio_astronomy)



**Grote Reber**  
(1911-2002)

**Karl Jansky** built (at Bell Telephone Laboratories) an antenna to receive radio waves at a frequency of 20.5 MHz ( $\lambda \sim 14.6\text{m}$ )  $\rightarrow$  "turntable" of 30m $\times$ 6m  $\rightarrow$  first detection of astronomical radio waves ( $\rightarrow 1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ )

**Grote Reber** extended Jansky's work and conducted the first radio sky survey. For nearly a decade he was the world's only radio astronomer.

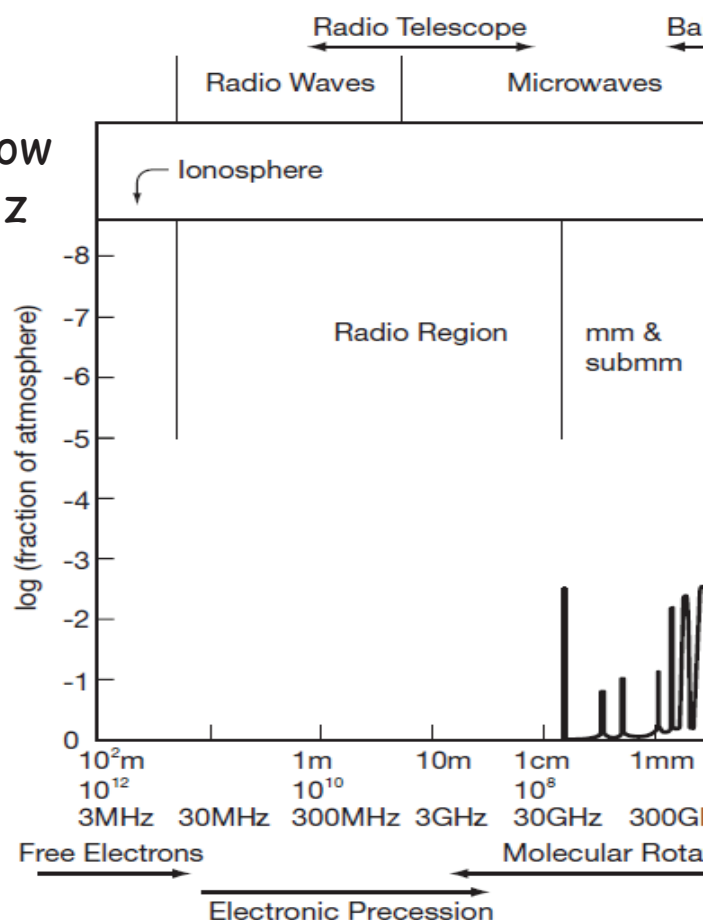


# Radio Astronomy led to the Discovery of ...

- the radio (synchrotron) emission of the Milky Way (1933)
- discrete cosmic radio sources, at first, supernova remnants and radio galaxies (1948)
- the 21 cm line of atomic hydrogen (1951)
- Quasi Stellar Objects (1963)
- Cosmic Microwave Background (1965)
- Interstellar molecules  $\Leftrightarrow$  Star formation (1968)
- Pulsars (1968)

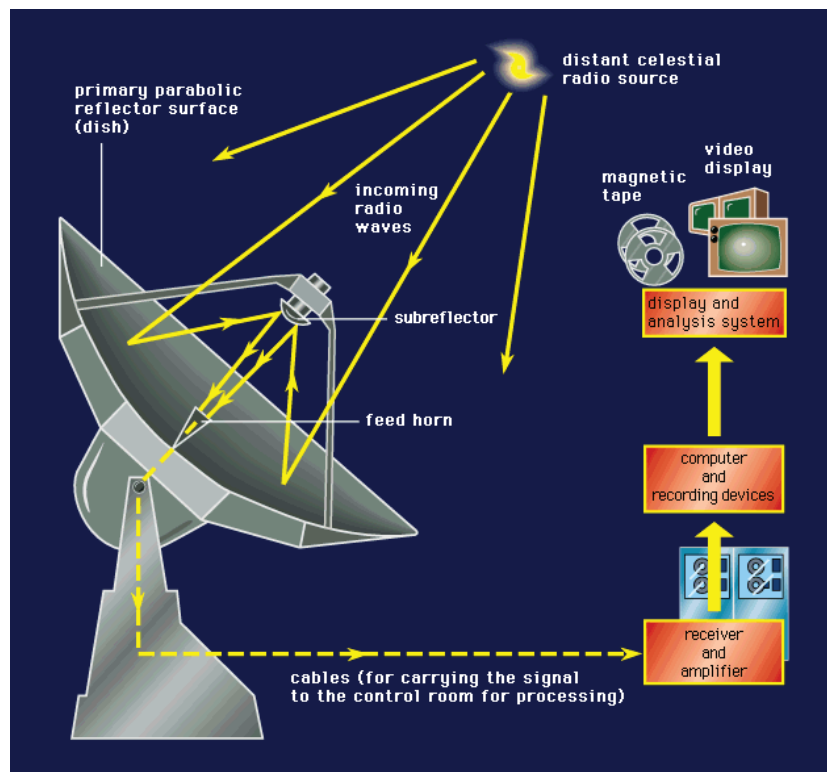
## Radio Observations through the Atmosphere

- The earth-bound radio window extends roughly from 10MHz (30m) to 1.5 THz (0.2mm).
- The low-frequency limit is given by the ionosphere
- the high frequency limit by molecular transitions of atmospheric  $H_2O$  and  $N_2$ .



# Radio Wavelengths: Photons→Electric Fields

*The longer radio wavelengths permit a more direct handling of the electric fields. Instead of using optical devices (lenses, etc.) to direct the photons, the electric fields excite currents in antennae and the signals can be amplified electrically.*



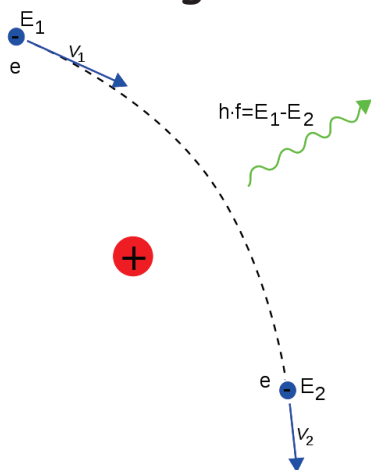
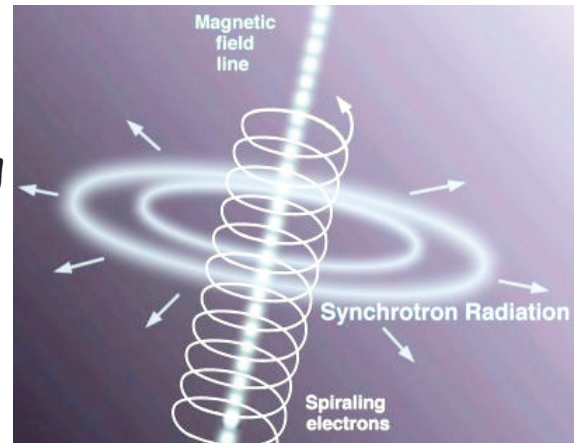
# RADIO EMISSION

# Radio Emission Mechanisms (1)

The main astronomical radio emission components are:

1. Synchrotron emission
2. Free-free emission or thermal Bremsstrahlung
3. Thermal emission from dust grains
4. Spectral lines

Synchrotron radiation is caused by highly relativistic electrons, spiraling around galactic magnetic field lines.

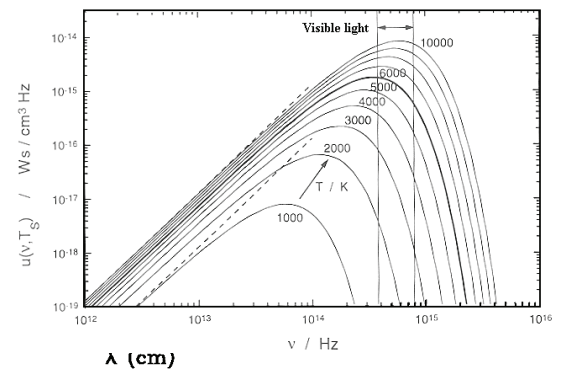


Free-free emission or thermal Bremsstrahlung is produced by free electrons scattering off (=accelerated) ions (e.g. in an HII region) without being captured.

# Radio Emission Mechanisms (2)

The Rayleigh-Jeans tail of the thermal (BB) emission from dust grains produces radio emission.

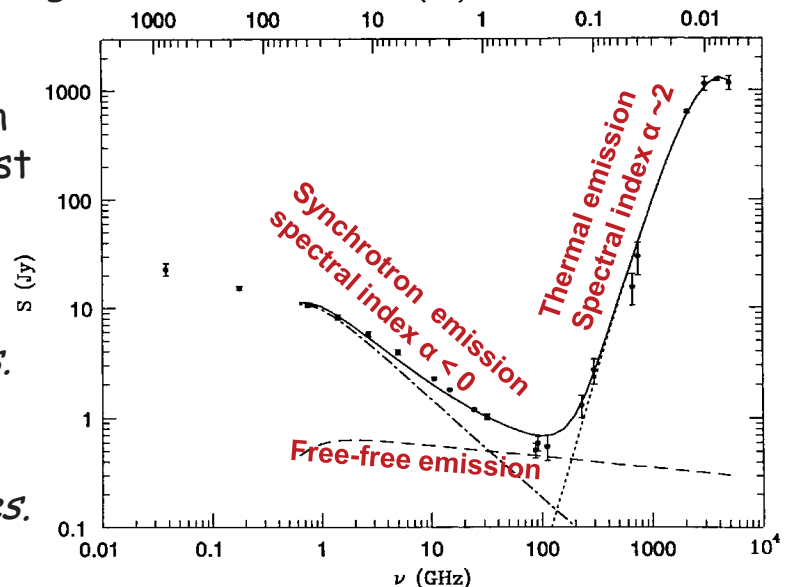
Spectral lines of molecules become more prominent at mm/sub-mm wavelengths. Most important is atomic hydrogen emission



Comparison of three emission components (for the starburst galaxy M82):

*Synchrotron radiation dominates at low frequencies.*

*Thermal dust emission dominates at high frequencies.*

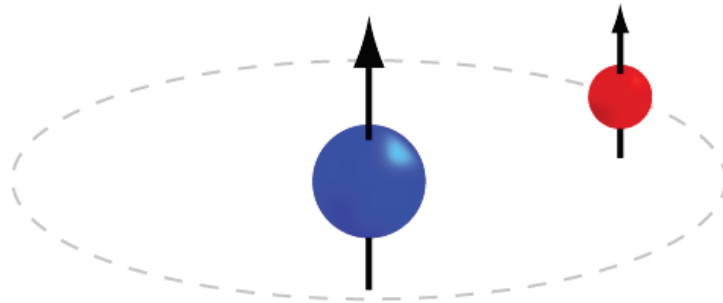
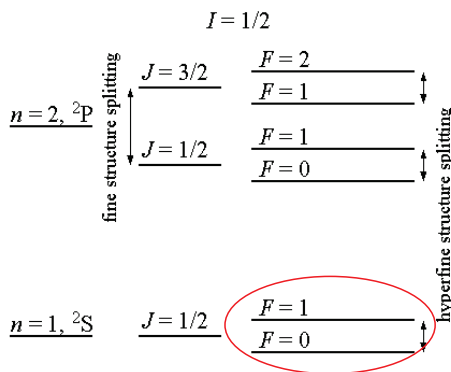


# The HI 21cm (1420.4 MHz) Line

Hendrik van de Hulst predicted in 1944 that neutral hydrogen could produce radiation at  $\nu = 1420.4$  MHz due to two closely spaced energy levels in the ground state of the hydrogen atom.



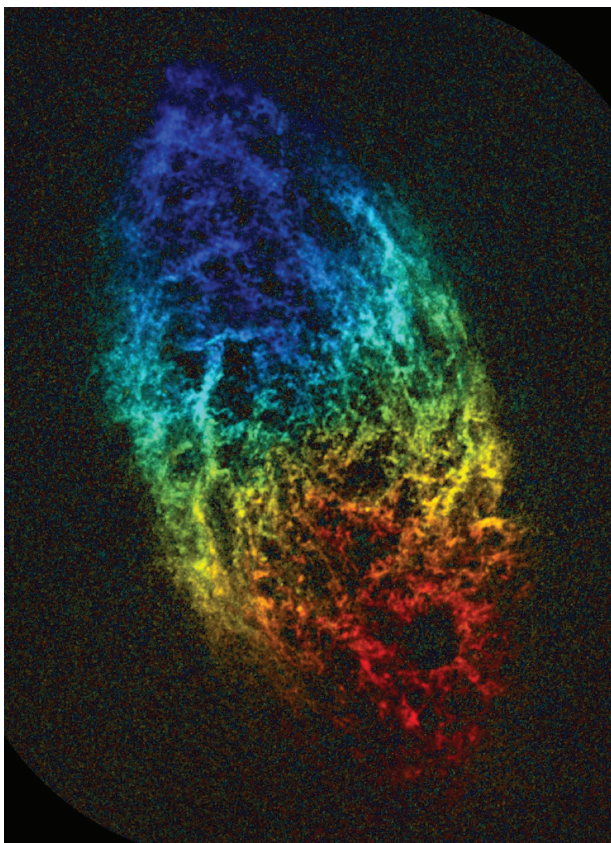
Hendrik van der Hulst  
(1918-2000)



First observed in 1951 by Ewen and Purcell at Harvard University, then by Dutch astronomers Muller and Oort

*After 1952 the first maps of the neutral hydrogen in the Galaxy were made and revealed, for the first time, the spiral structure of the Milky Way.*

## Astronomical Relevance of the HI 21cm Line



Two main applications:

1. Distribution of atomic gas in galaxies (e.g.,  $\leftarrow$  M33)
2. Big Bang cosmology: redshifted HI line can be observed from 200 MHz to about 9 MHz:
  - mapping redshifted 21 cm provides the matter power spectrum after recombination
  - provides info on how the Universe was reionized (HI which has been ionized by stars or quasars will appear as holes)

*But the signals are intrinsically weak and plagued by radio interferences.*

*The HI radial velocity field of the nearby spiral galaxy M33 is shown here by colors corresponding to Doppler redshifts and blueshifts relative to the center of mass; brightness in this image is proportional to HI column density. Thilker, Braun & Walterbos (1998)*

# OBSERVING IN THE RADIO

## Dispersion Measure

If a variable compact source (e.g., a pulsar) emits all frequencies at once, the arrival times of the different frequencies is affected the interstellar medium (ISM).

For an ionized ISM of path length  $L$  and electron density  $N$ , the so-called **dispersion measure** is

$$DM = \int_0^L \left( \frac{N}{\text{cm}^{-3}} \right) d \left( \frac{l}{\text{pc}} \right)$$

and the relative time delay is:  $\frac{\Delta\tau_D}{\mu\text{s}} = 1.34 \times 10^{-9} \left[ \frac{\text{DM}}{\text{cm}^{-2}} \right] \left[ \frac{1}{\left( \frac{\nu_1}{\text{MHz}} \right)^2} - \frac{1}{\left( \frac{\nu_2}{\text{MHz}} \right)^2} \right]$

(lower frequencies are delayed more)

→ good technique to measure either electron densities or distances

# Faraday Effect and Rotation Measure

The **Faraday effect** is caused by the interaction between light and a magnetic field in a medium and results in a the rotation of the plane of polarization.

The Faraday effect causes left and right circularly polarized waves to propagate at slightly different speeds.

Since linear polarization can be decomposed into two circularly polarized components, the Faraday effect rotates the angle of the linear polarization.

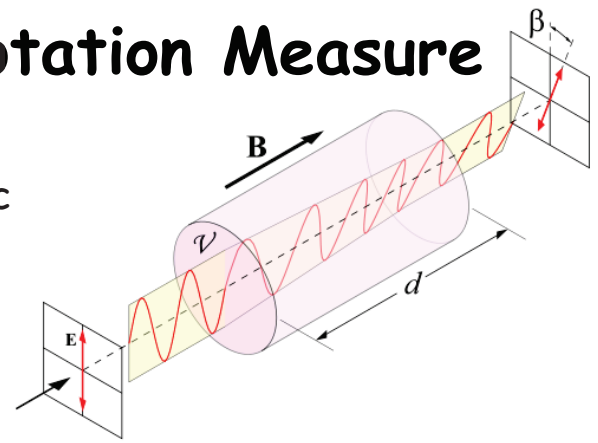
In the ISM, the effect is **caused by free electrons** and has a simple dependence on the wavelength of light ( $\lambda$ ):

$$\beta = RM \cdot \lambda^2$$

The **rotation measure** RM characterizes the overall strength and is given by:

$$RM = \frac{e^3}{2\pi m^2 c^4} \int_0^L n_e(s) B_{\parallel}(s) ds$$

Hence, it can be used to measure the **magnetic field strength**  $B_{\parallel}$ .



# ANTENNA TECHNOLOGY



# Famous Radio Telescopes (Single Dish)



## Antennae: The Hertz Dipole

*Antennae are required to focus power into the feed, a device that efficiently transfers power in the electromagnetic wave to the receiver.*

*The properties of antennae (beam patterns, efficiencies, ...) are the same for transmission and reception.*

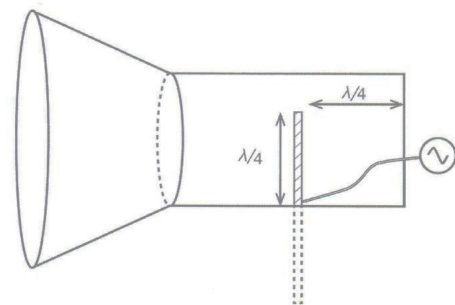
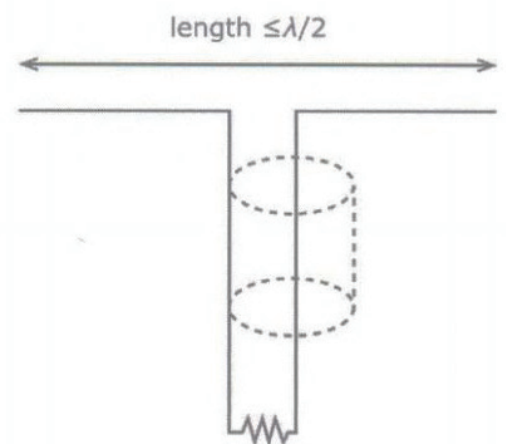


Figure 8.14. A feedhorn with a ground-plane vertical as the antenna. The ground plane vertical creates a full dipole antenna by reflection of one half of such an antenna.

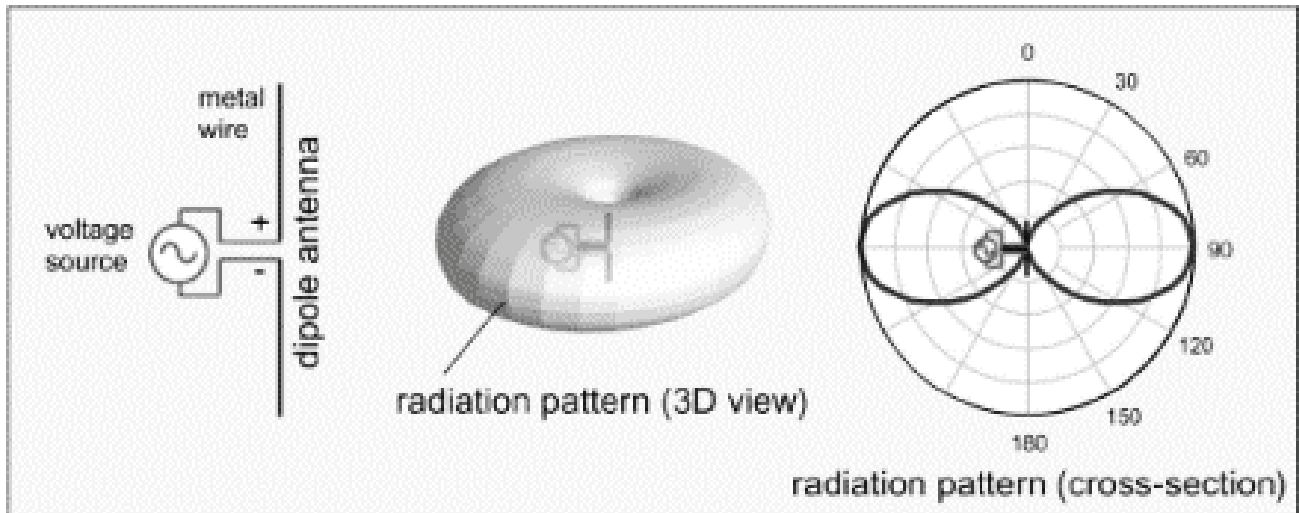
Let's consider a **Hertz dipole**:  
The total power radiated from a Hertz dipole carrying an oscillating current  $I$  at a wavelength  $\lambda$  is:

$$P = \frac{2c}{3} \left( \frac{I\Delta l}{2\lambda} \right)^2$$



# Radiation from a Hertz Dipole

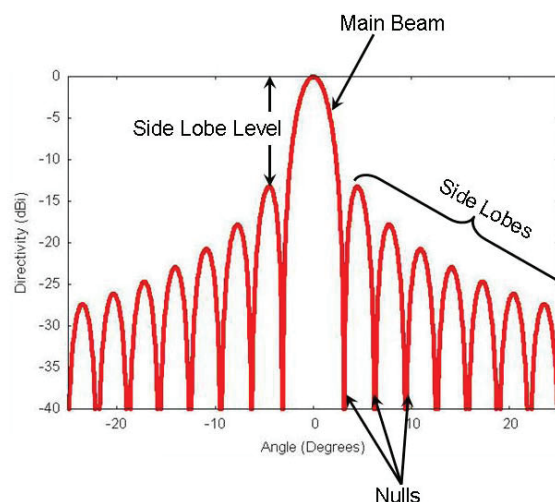
- The radiation is linearly polarized
- Electric field lines are along the direction of the dipole
- Radiation pattern has a donut shape and is defined by the zone where the phases match sufficiently well to combine constructively
- Along the direction of the dipole, the field is zero
- Best efficiency when the size of the dipole is  $1/2 \lambda$ .



## Radio Beams, PSFs and "Lobes"

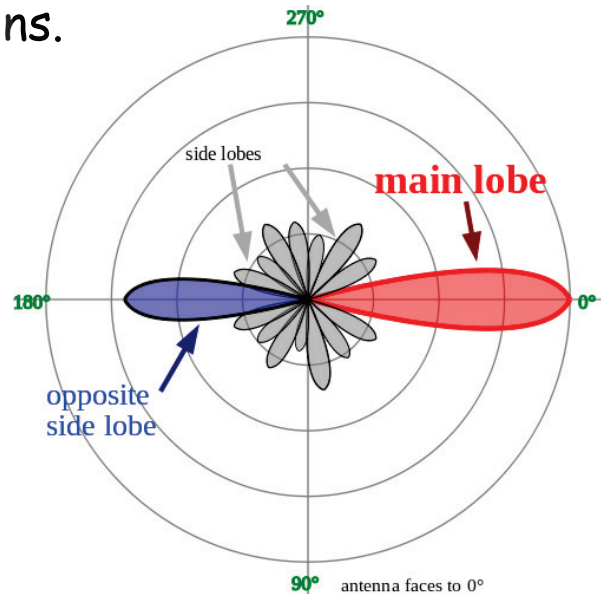
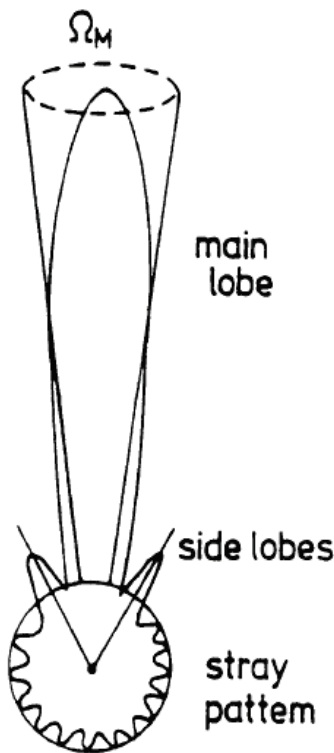
Similar to optical telescopes, the **angular resolution** is given by  $\theta = k \frac{\lambda}{D}$  where  $k \sim 1$ .

Radio beams show - just like the Airy patterns of optical PSFs - patterns of "**lobes**" at various angles, directions where the radiated signal strength reaches a maximum, separated by "**nulls**", angles at which the radiated signal strength falls to zero.



# Main Beam and Sidelobes

The largest field strength is in the "main lobe", the other lobes are called "sidelobes", and usually represent unwanted radiation in undesired directions.



Side lobes may pick up interfering signals, and increase the noise level in the receiver. The side lobe in the opposite direction (180°) from the main lobe is called the "back lobe".

## Main Beam Efficiency

The **beam solid angle**  $\Omega_A$  in steradians of an antenna is given by:

$$\Omega_A = \iint_{4\pi} P_n(\vartheta, \varphi) d\Omega = \int_0^{2\pi} \int_0^{\pi} P_n(\vartheta, \varphi) \sin \vartheta d\vartheta d\varphi$$

With the normalized power pattern  $P_n(\vartheta, \varphi) = \frac{1}{P_{\max}} P(\vartheta, \varphi)$

Hence,  $P_n = 1$  for  $\Omega_A$  for an ideal antenna.

Analogously, the **main beam solid angle**  $\Omega_{MB}$  is:

$$\Omega_{MB} = \iint_{\text{main lobe}} P_n(\vartheta, \varphi) d\Omega$$

And the **main beam efficiency**  $\eta_B$  is:  $\eta_B = \frac{\Omega_{MB}}{\Omega_A}$

(This is the fraction of the power concentrated in the main beam.)

# RECEIVER TECHNOLOGY

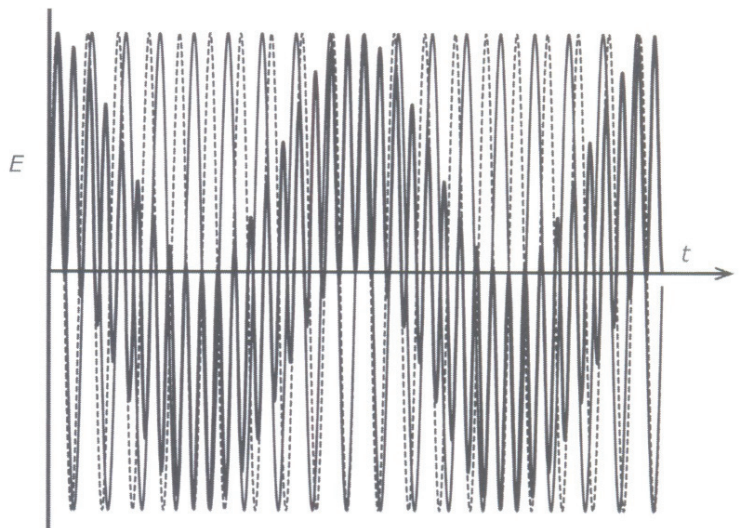
## Coherent (Heterodyne) Receivers

We want to detect and amplify signals (electromagnetic waves). Problems:

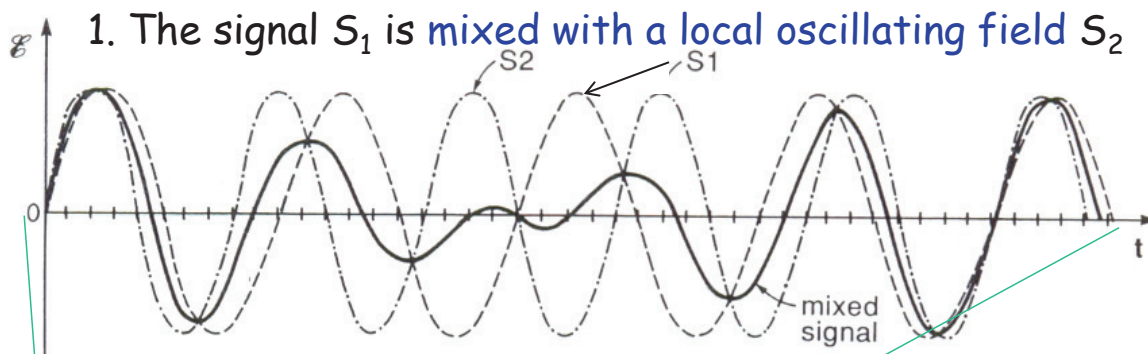
1. The signals are usually very weak
2. The frequencies are too high for standard electronics

|                             |   |   |
|-----------------------------|---|---|
| $\lambda = 1 \mu\text{m}$   | $\Leftrightarrow \nu = 300 \text{ THz}$ | $\Leftrightarrow \Delta t = 3.3 \cdot 10^{-15} \text{ s}$ |
| $\lambda = 100 \mu\text{m}$ | $\Leftrightarrow \nu = 3 \text{ THz}$   | $\Leftrightarrow \Delta t = 3.3 \cdot 10^{-13} \text{ s}$ |
| $\lambda = 1 \text{ cm}$    | $\Leftrightarrow \nu = 30 \text{ GHz}$  | $\Leftrightarrow \Delta t = 33 \text{ ps}$                |

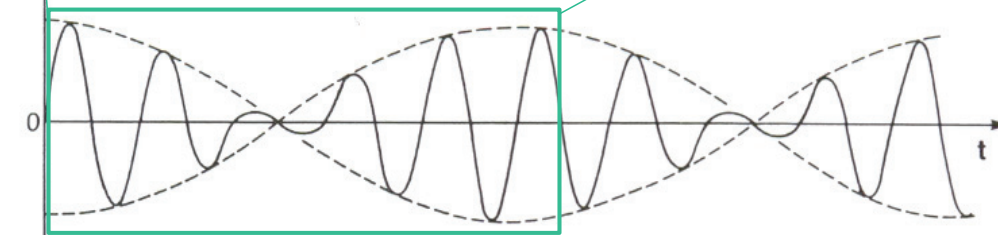
Solution: **Mixing** of the source signal with a reference wave (provided by a **local oscillator**):



# Principle of Frequency Mixing



2. The mix produces a down-converted difference, intermediate, or "beat" frequency at  $\omega_{S1} - \omega_{S2}$  (and  $\omega_{S1} + \omega_{S2}$ ).

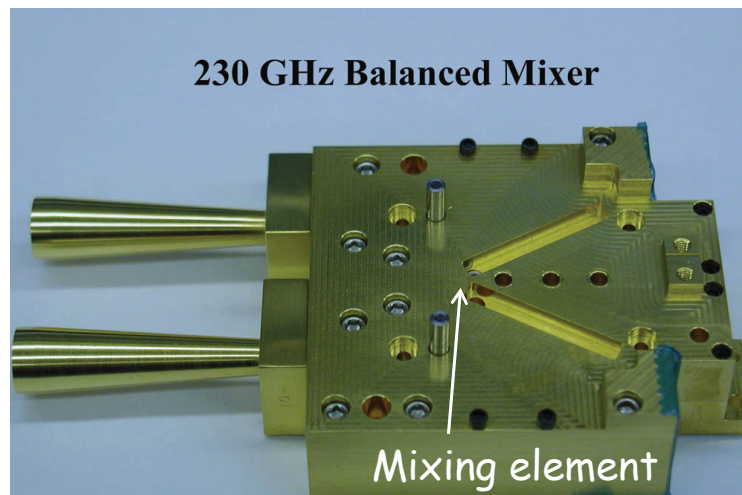


- encodes signal over a wide wavelength range → ideal for spectroscopy
- typically,  $\text{power}(\omega_{LO}) \gg \text{power}(\omega_S)$  → amplification by oscillator signal
- down-conversion to frequencies where low-noise electronics exist.

## Mixer Technology

Example of a mixer:

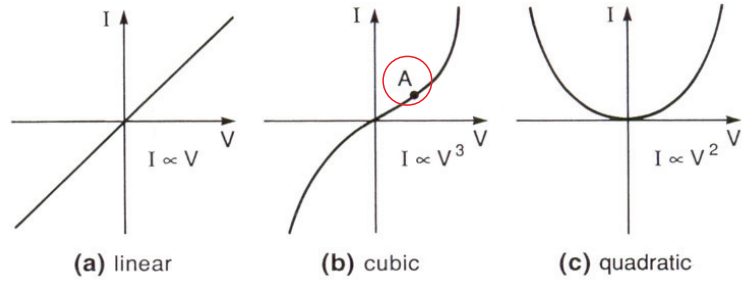
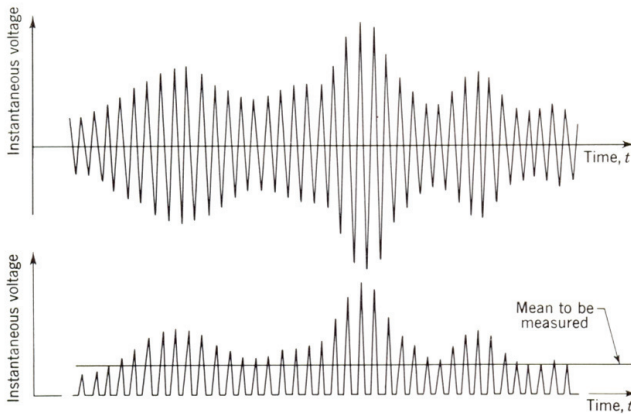
Source signal →  
Local oscillator signal →



**Problem:** good & fast "traditional" photo-conductors do not exist for  $\nu < 7.5$  THz

- 
- Schottky diodes
  - SIS junctions
  - Hot electron bolometers

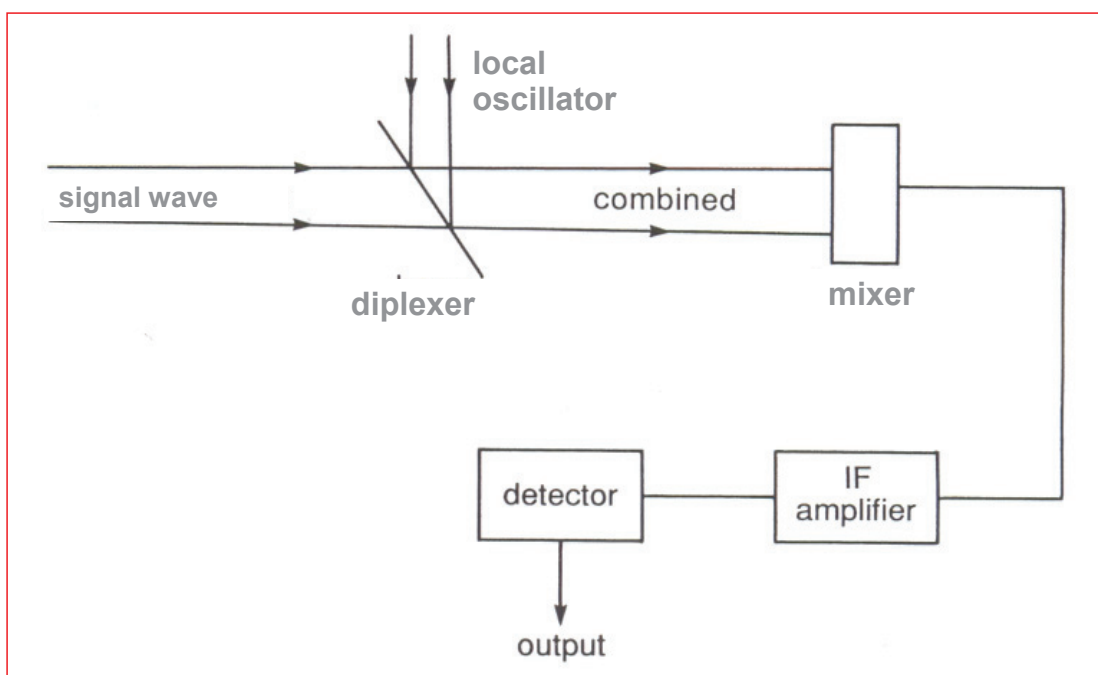
# The Mixer Output



- A linear device (a) yields no output power at any frequency.
- a non-linear device (b,c) can convert power from the original frequencies to the beat frequency
- even if the mixer has an odd function of voltage around the origin (b) the conversion efficiency is zero.
- but if biased above zero (A) the average change in current is larger for positive than for negative voltage peaks.

If  $I \sim V^2$  (as in a diode) then output  $\sim (\text{field strength})^2 \sim \text{power}$ , which is exactly what we want to measure!

## Basic Principle of a Heterodyne System



# BACK ENDS

The term "Back End" is used to specify the devices following the IF amplifiers. Many different back ends have been designed for specialized purposes such as continuum, spectral or polarization measurements.

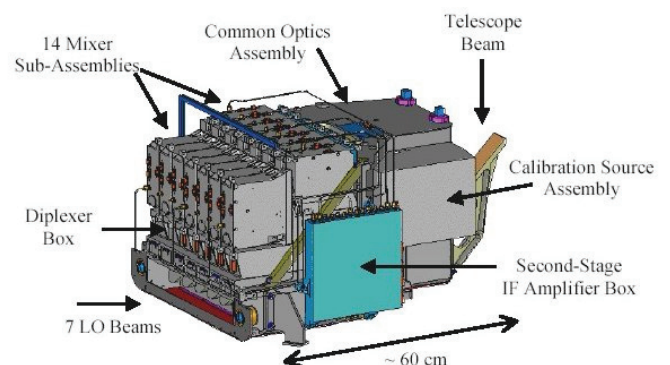
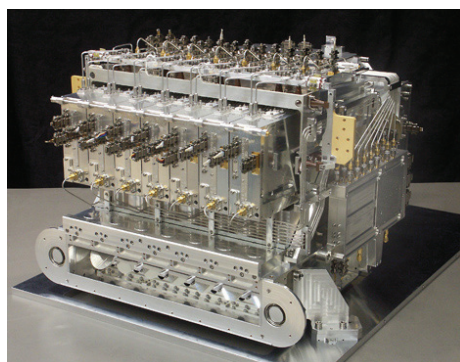
## Polarimeters

Antennas with a fixed-dipole feeder or horn feeder receive only the fraction that is polarized in the plane of the orientation of the feeder.

Rotation can be measured by rotating the feeder about the antenna's beam axis or by two orthogonally polarized antenna feeders.

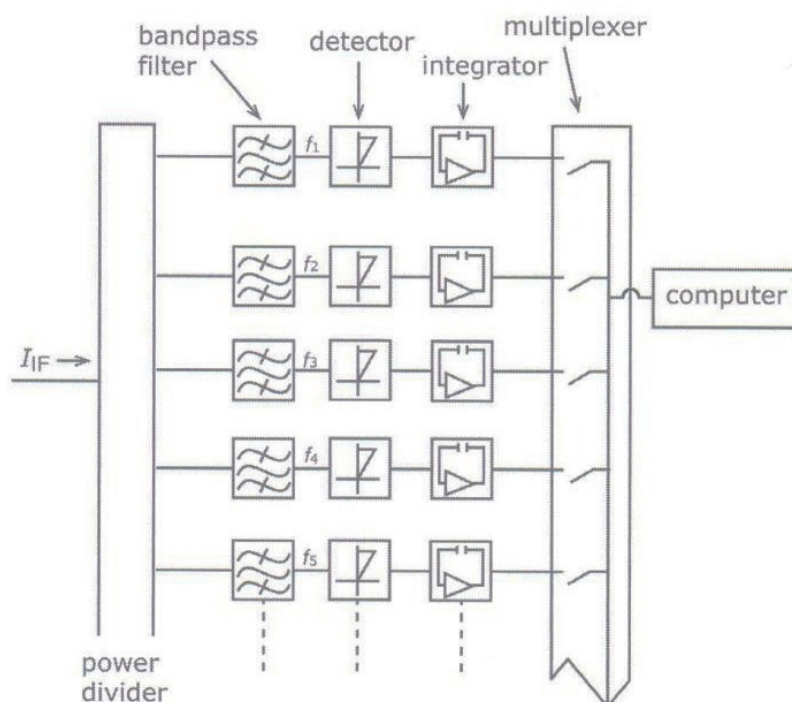
Heterodyne dual polarization receiver = two identical systems, connected to the same local oscillator, and sensitive to only one of the two orthogonal polarizations.

Such a polarimeter can provide values of all four Stokes parameters simultaneously.



# Multichannel Spectrometer

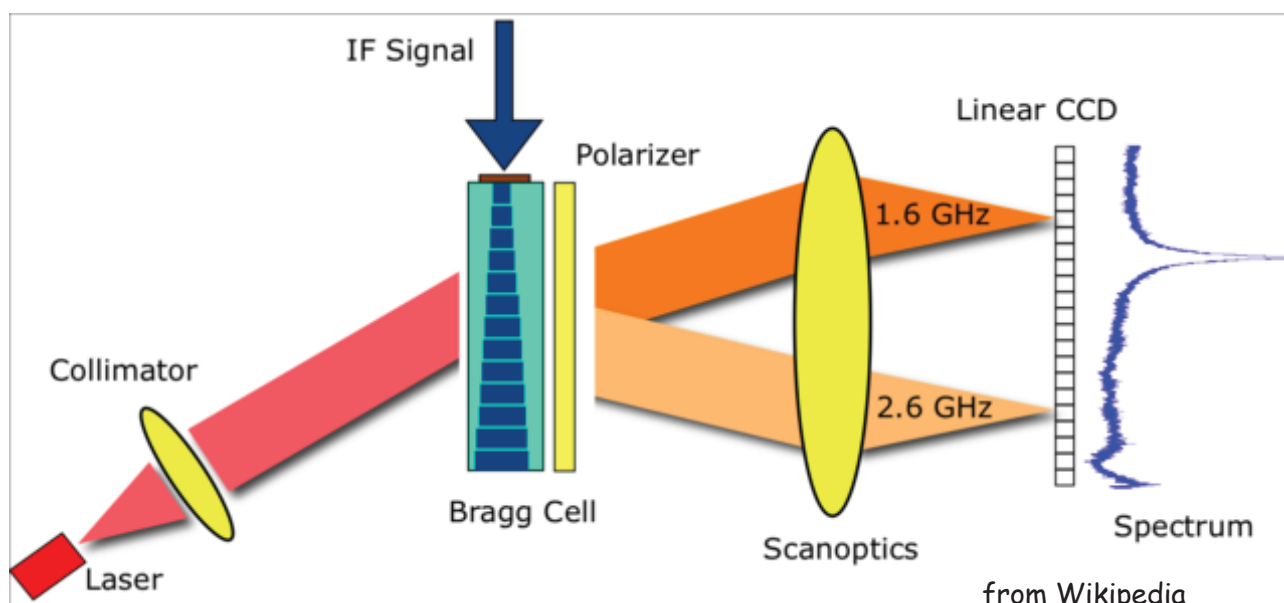
The IF input signal is divided among the bandpass filters ("filter bank") and the output of each is processed by a detector/integrator stage. The outputs of these stages are switched sequentially to the computer where the spectrum can be displayed.



Such multi-channel spectrometers can have up to 512 parallel channels.

# Acousto-Optical Spectrometer

An AOS converts the frequencies to ultrasonic waves that disperse a monochromatic light beam onto an array of visible light detectors.



from Wikipedia

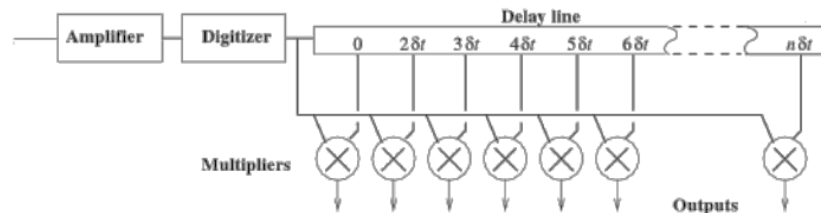
The acoustic wave can be created in a crystal ("Bragg-cell") and modulates the refractive index  $\rightarrow$  induces a phase grating. The angular dispersion is a measure of the IF-spectrum.



# Autocorrelation Spectrometer

|           |  |  |
|-----------|--|--|
| Reminder: | $f(x)$   | Function                                     |
|           | $\tilde{f}(s) = FT\{f(x)\}$                    | Fourier transform of $f(x)$                  |
|           | $ \tilde{f}(s) ^2$                             | Spectral density or power spectrum of $f(x)$ |
|           | $ \tilde{f}(s) ^2 = f(x) \otimes f(x)$         | Wiener - Khinchine (autocorrelation) theorem |
|           | $k(x) = \int_{-\infty}^{+\infty} f(u)f(u+x)du$ | Autocorrelation                              |

1. We have: time dependent IF signal  $f(x)$
2. We want: Power spectrum  $I(\nu) = |f(s)|^2$
3. We know:  $|f(s)|^2$  can be computed via  $FT\{f(x)\}$
4. Better and faster: compute autocorrelation function of  $f(x)$
5. → Digitize and delay  $x(t)$   $n$ -times and compute autocorrelation



# CALIBRATIONS

# "True" Brightness Temperature

Remember the Rayleigh-Jeans approximation :

$$B_{RJ}(\nu, T) = \frac{2\nu^2}{c^2} kT$$

i.e., brightness and effective temperature are strictly proportional.

Hence, we can use the **brightness temperature** to describe the source intensity:

$$T_B = \frac{c^2}{2k\nu^2} B_{RJ} = \frac{\lambda^2}{2k} B_{RJ}$$

Note that this is usually only fulfilled if the source fills the beam, i.e., for very extended sources.

- If the source is a real black body  $h\nu \ll kT$ , then  $T_B$  is independent of  $\nu$ .
- If the emission is non-BB (e.g., synchrotron, free-free, ...)  $T_B$  will depend on  $\nu$  but the brightness temperature is still being used.

## Main Beam Brightness Temperature

Remember the relation between flux density  $S_\nu$  and intensity  $I_\nu$ :

$$S_\nu = \int_{\Omega_B} I_\nu(\theta, \varphi) \cos \theta \, d\Omega$$

Hence, for discrete sources, the source extent is important and we need to combine the above equation with the previous one to:

$$S_\nu = \frac{2k\nu^2}{c^2} T_B \cdot \Delta\Omega$$

... or simplified for a source with a Gaussian shape:

$$\left[ \frac{S_\nu}{\text{Jy}} \right] = 0.0736 T_B \left[ \frac{\theta}{\text{arcsec}} \right]^2 \left[ \frac{\lambda}{\text{mm}} \right]^{-2}$$

Generally, for an antenna beam size  $\theta_{\text{beam}}$  the observed source size is:

$$\theta_{\text{observed}}^2 = \theta_{\text{source}}^2 + \theta_{\text{beam}}^2$$

...which relates the true brightness temperature with the **main beam**

**brightness temperature:**  $T_{MB}(\theta_{\text{source}}^2 + \theta_{\text{beam}}^2) = T_B \theta_{\text{source}}^2$

# Noise Temperature

The power spectral density (PSD) entering the receiver is given by

$$P_v = kT$$

...and is also called **antenna temperature**.

A receiver shall increase the input power level. The amplification involves a **noise factor  $F$** , defined via the S/N as:

$$F = \frac{S_{input} / N_{input}}{S_{output} / N_{output}}$$

For coherent receivers this noise factor is expressed as **noise temperature**:

$$T_R = (F - 1) \cdot 290K$$

## Receiver Calibration

The **noise temperature** or **receiver temperature** can be measured by comparing the signals of two loads with the two effective temperatures  $T_1$  and  $T_2$ . The total power output is given by:

$$P_1 = \alpha(T_R + T_1) \quad \text{and} \quad P_2 = \alpha(T_R + T_2)$$

...where  $\alpha = Gk\delta\nu$  and depends on the gain  $G$  and the bandwidth  $\delta\nu$ .

Now we can define a **Y-factor** as:  $Y = \frac{P_2}{P_1}$

With the Y-factor and solving for the **receiver temperature  $T_R$**  we get:

$$T_R = \frac{T_2 - YT_1}{Y - 1}$$

# Receiver Stability and Dicke Switching

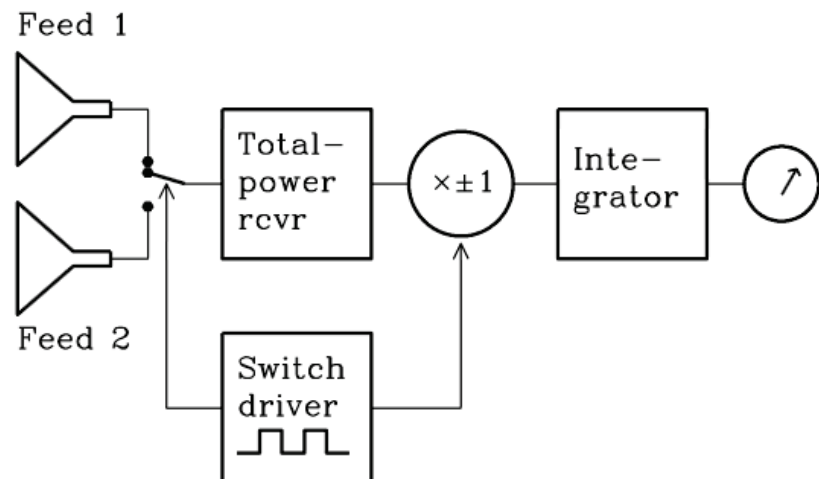
Source signals are weak  $\rightarrow$  gain must be high  $\rightarrow$  small gain instabilities can dominate the thermal receiver noise.

$\rightarrow$  Compare source signal with a stable reference signal by "beam switching" or "Dicke switching" (1946). It also compensates for atmospheric changes.

Disadvantage: 1/2 of the total time is spent to look at a flux reference.



Robert Henry Dicke  
(1916-1997)



## Spectral Line Observations

To detect weak spectral lines, three observing modes are commonly used:

1) **Position Switching and Wobbler Switching**. The signal "on source" is compared with a measurement of a nearby "sky position". Obviously, there should be no line radiation coming from the "sky position".

2) **On the Fly Mapping** (extension of method (1)): spectral line data is taken at a rate of perhaps one spectrum or more per second while the telescope slews (scans) continuously across the source field. The background/continuum emission is reconstructed from the entire data set.

3) **Frequency Switching**. For most sources, the spectral line radiation is restricted to a narrow band. Changing the frequency of the receiver on a short time by  $\sim 10\Delta\nu$  produces a comparison signal with the line well shifted. The line is measured all of the time, so this is an efficient observing mode.