Lecture 7: Radio

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Overview

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

The First Radio Astronomers

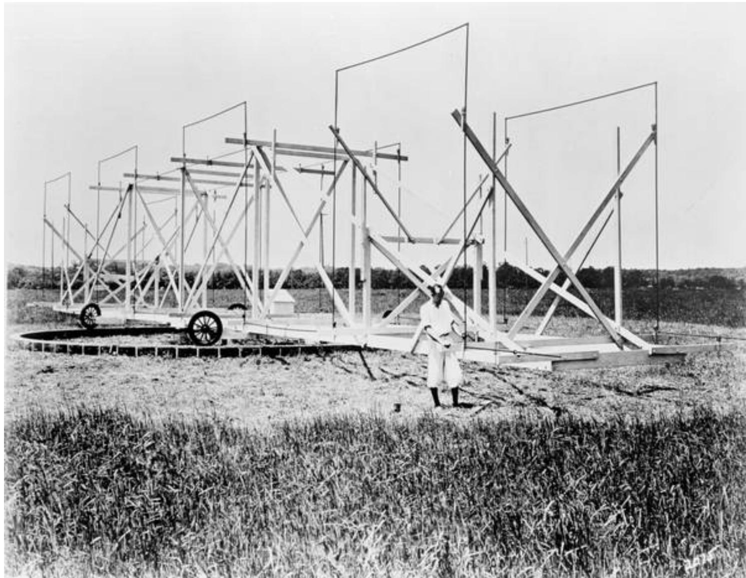
http://en.wikipedia.org/wiki/Radio_telescope
http://en.wikipedia.org/wiki/Radio_astronomy

Grote Reber (1911-2002)

Karl Guthe Jansky (1905-1950)

Karl Jansky built (at Bell Telephone Laboratories) antenna to receive radio waves at 20.5 MHz (λ~14.6m) → "turntable" of 30m×6m → first detection of astronomical radio waves (→ 1 Jy = 10^{-26} W m^{-2} Hz^{-1})

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

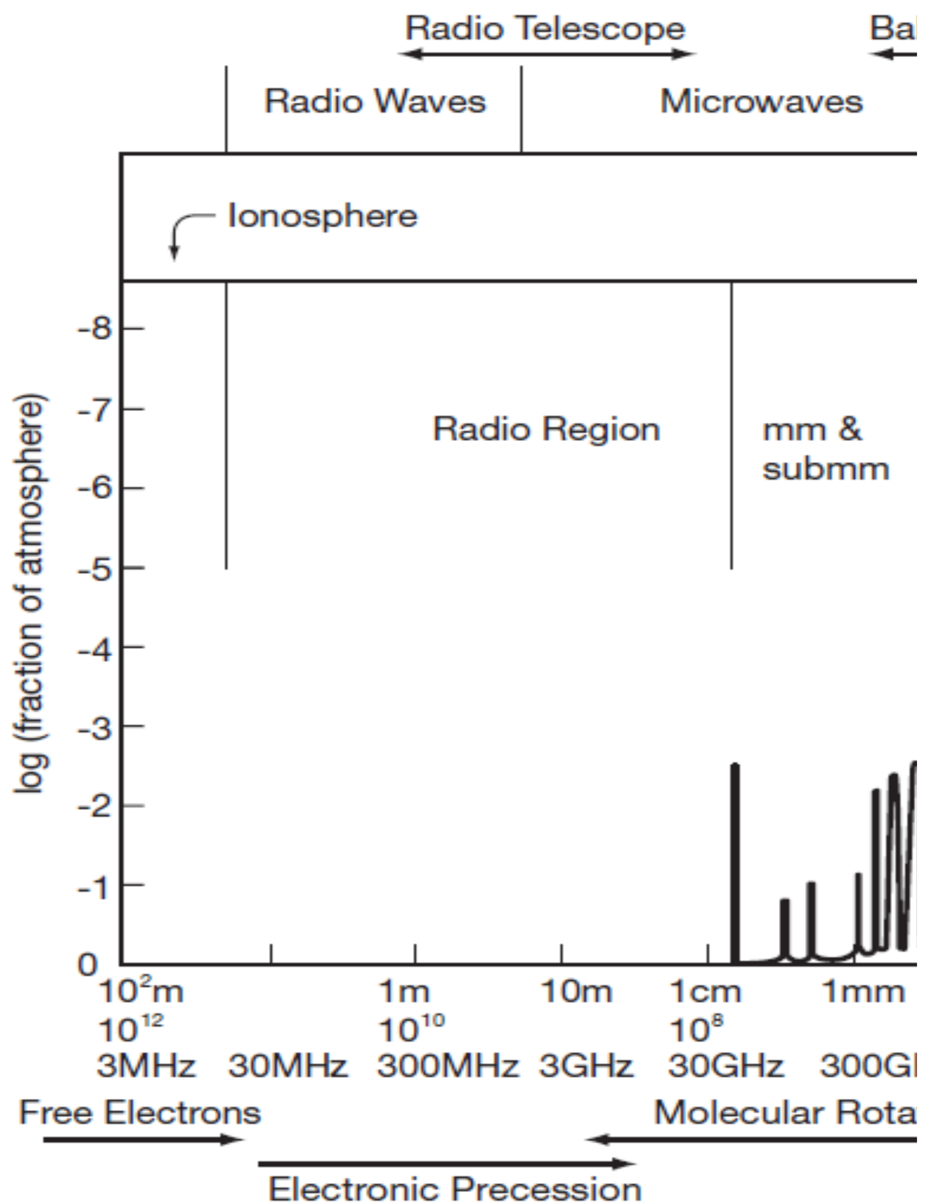


Radio Astronomy Discoveries

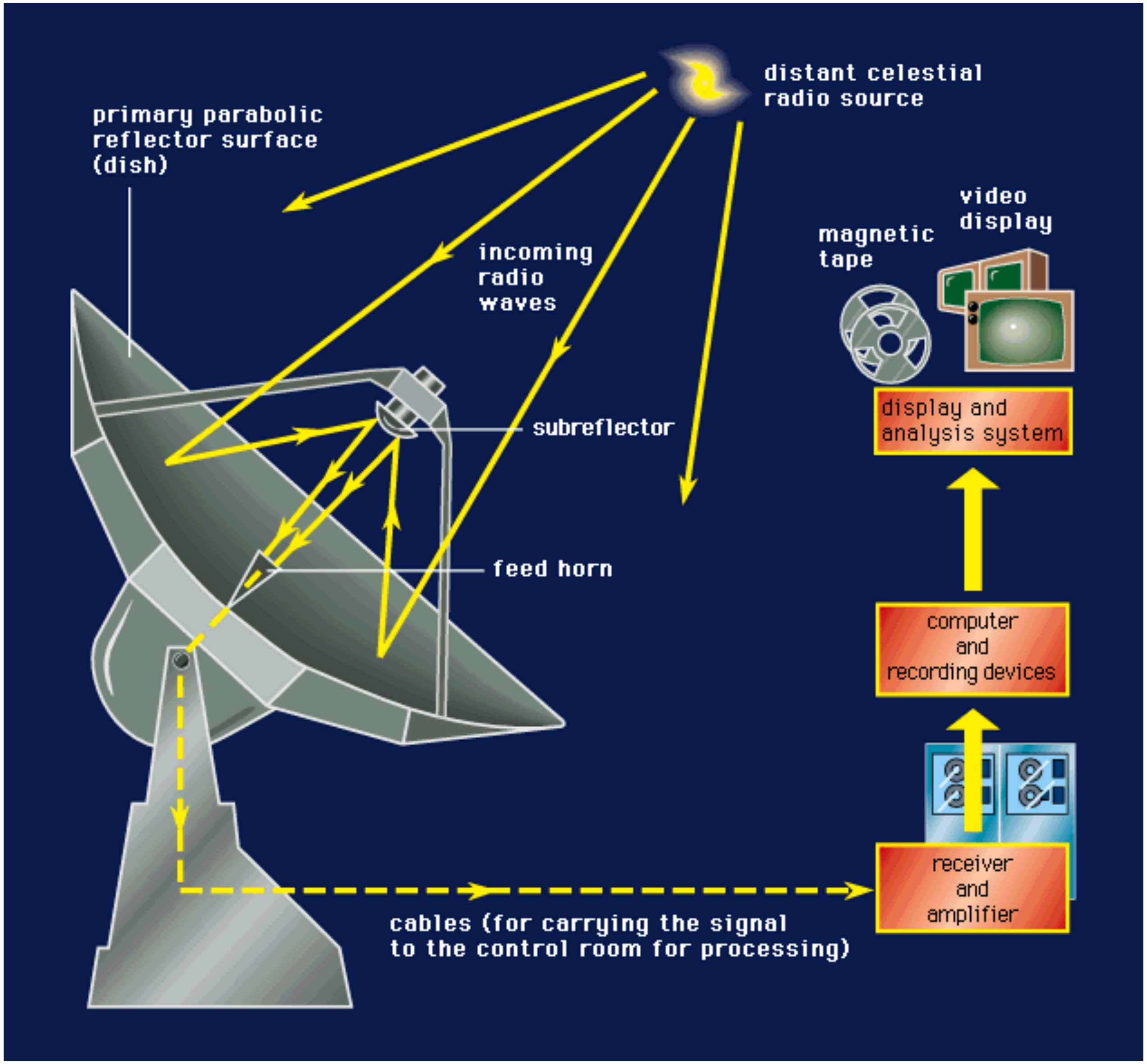
- radio (synchrotron) emission of the Milky Way (1933)
- first discrete cosmic radio sources: supernova remnants and radio galaxies (1948)
- 21-cm line of atomic hydrogen (1951)
- Quasi Stellar Objects (1963)
- Cosmic Microwave Background (1965)
- Interstellar molecules ⇔ star formation (1968)
- Pulsars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

Radio Observations through the Atmosphere

- Radio window from ~10 MHz (30m) to 1 THz (0.3mm)
- Low-frequency limit given by (reflecting) ionosphere
- High frequency limit given by molecular transitions of atmospheric H_2O and N_2.



Radio: Photons→Electric Fields



- Directly measure electric fields of electro-magnetic waves
- Electric fields excite currents in antennae
- Currents can be amplified and split electrically.

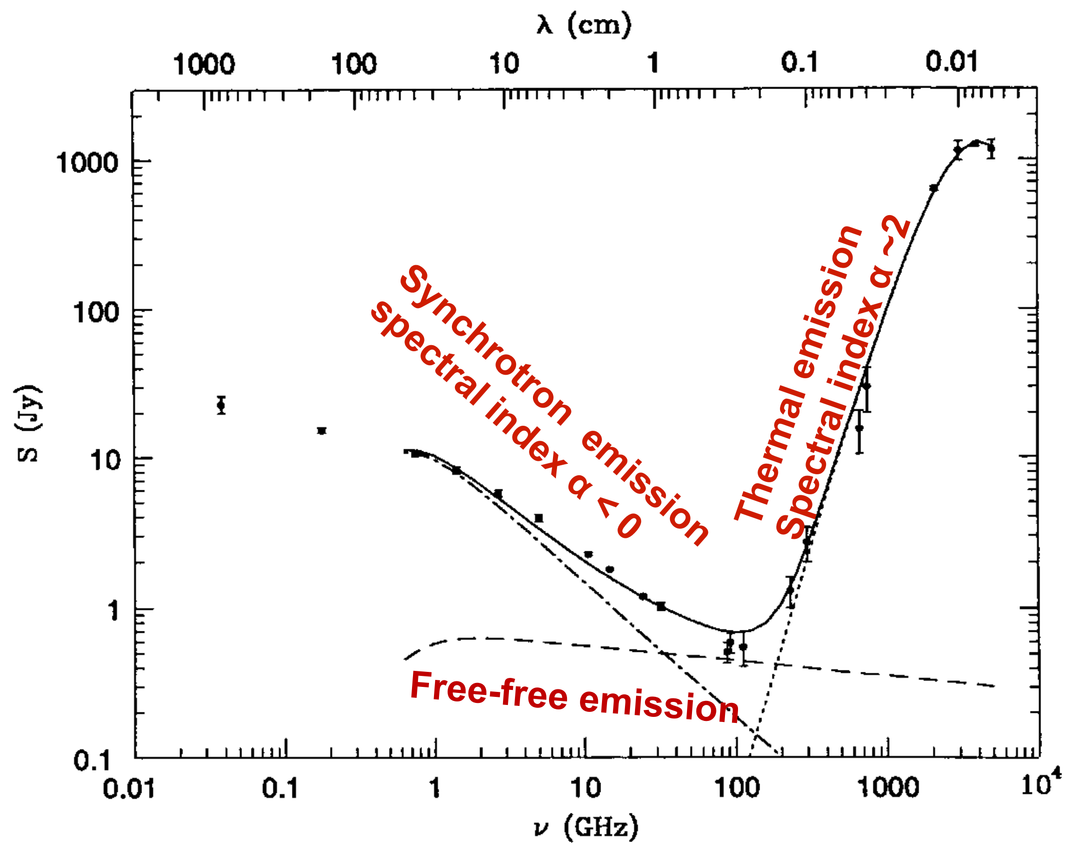
Radio Emission Mechanisms

Most important astronomical radio emission mechanisms

1. Synchrotron emission
2. Free-free emission (thermal Bremsstrahlung)
3. Thermal (blackbody) emission (also from dust grains)
4. Spectral lines

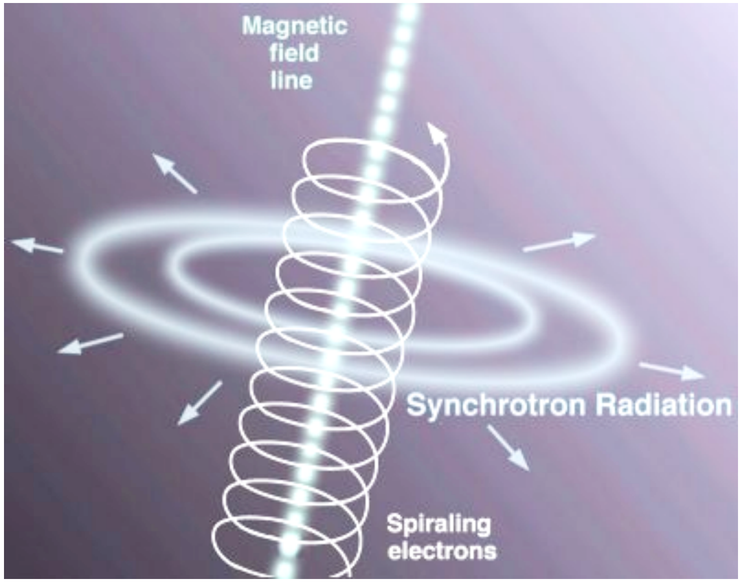
Comparison of three emission components (for the starburst galaxy M82)

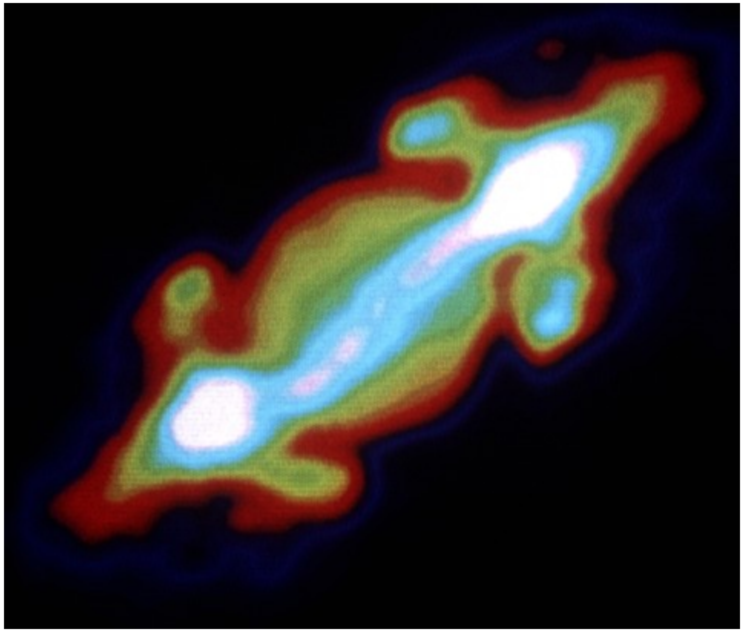
- Synchrotron radiation dominates at low frequencies.
- Thermal dust emission dominates at high frequencies.



Synchrotron Emission

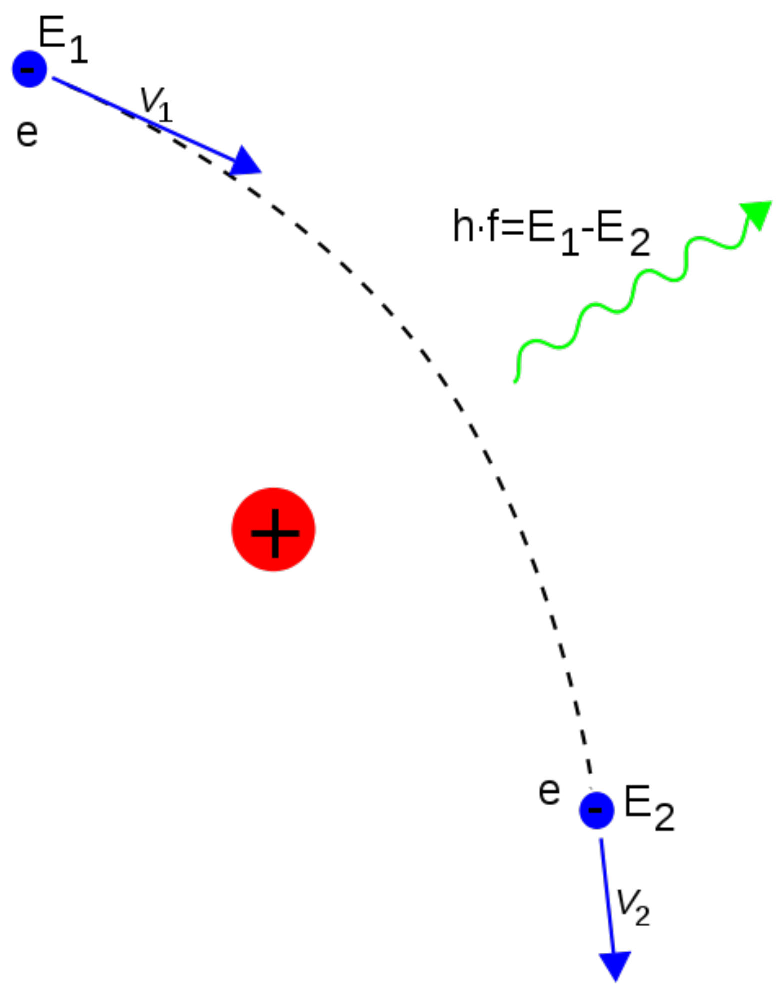
- Caused by highly relativistic electrons, spiraling around galactic magnetic field lines
- Polarized
- Continuous spectrum



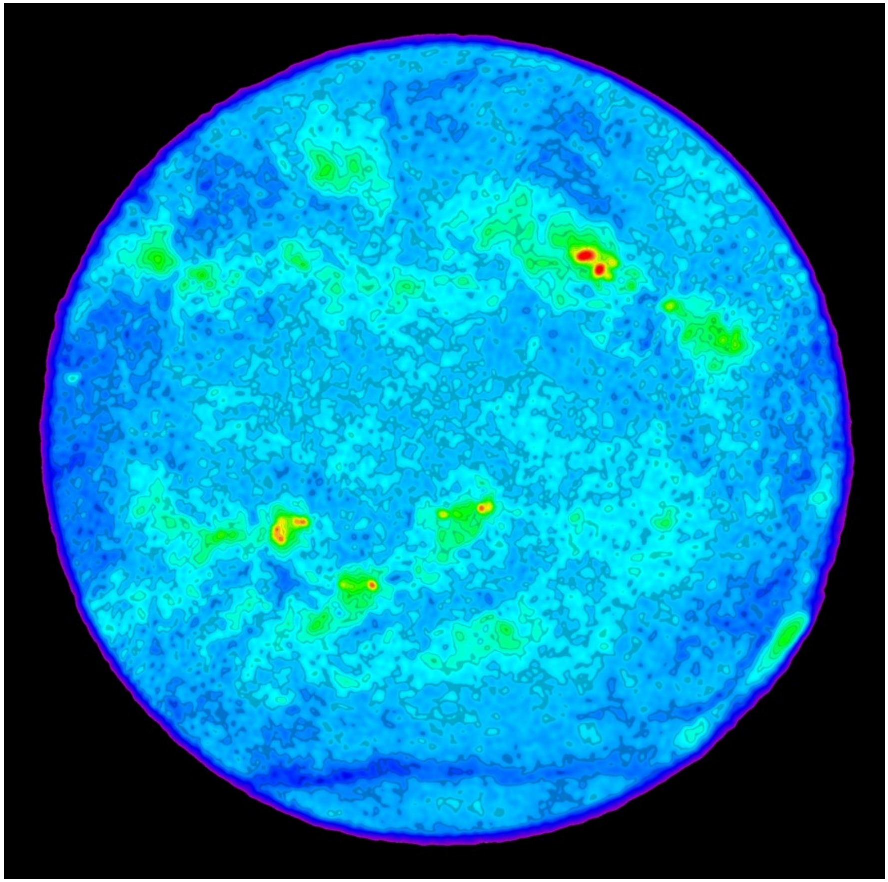


http://www.cv.nrao.edu/course/astr534/images/Jupiter.jpg

Free-Free Emission



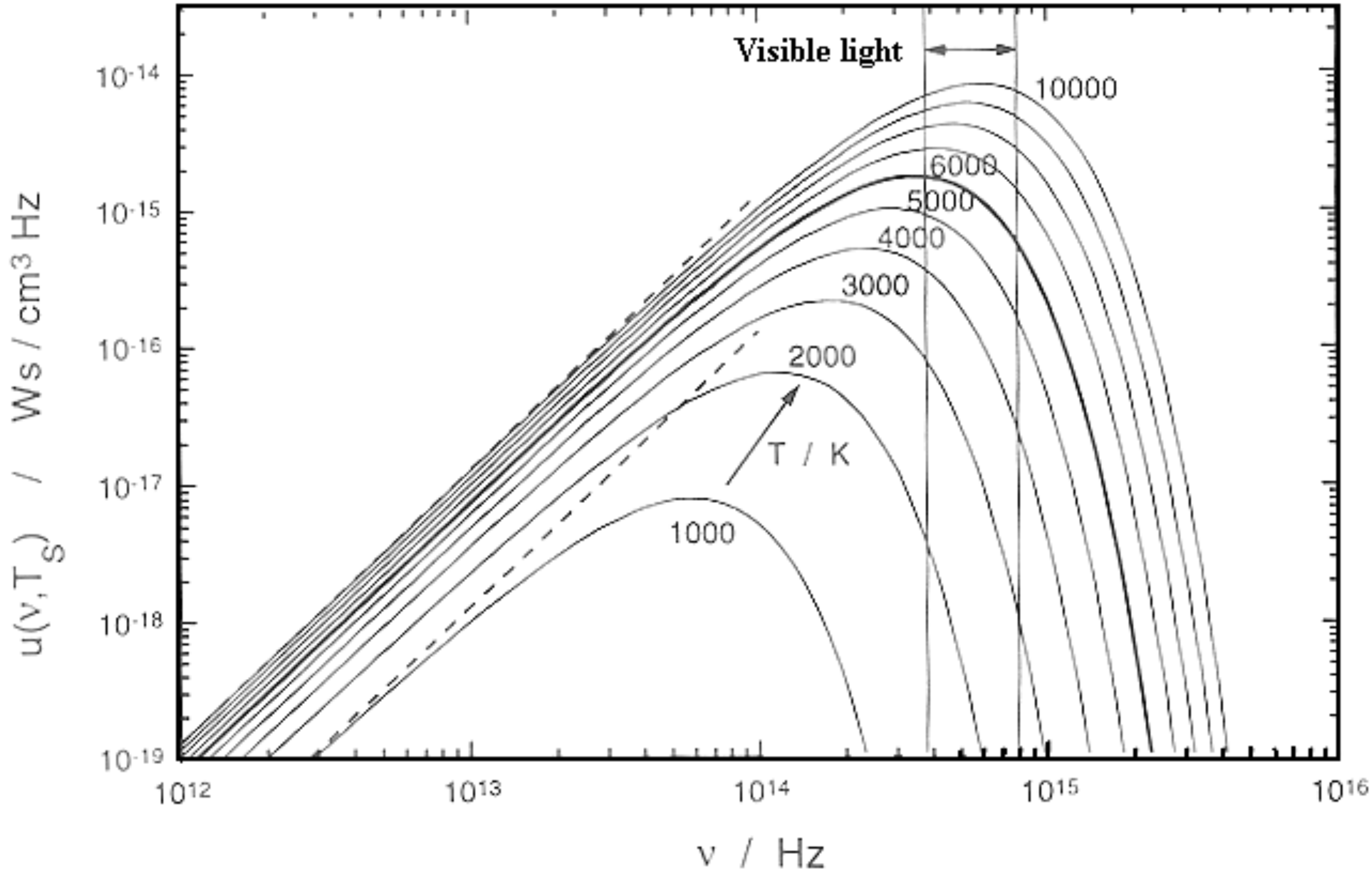
Free-free emission produced by free electrons scattering off ions (e.g. in HII regions) without being captured: continuous spectrum



http://www.cv.nrao.edu/course/astr534/images/Sun5GHz.jpg

Thermal Emission

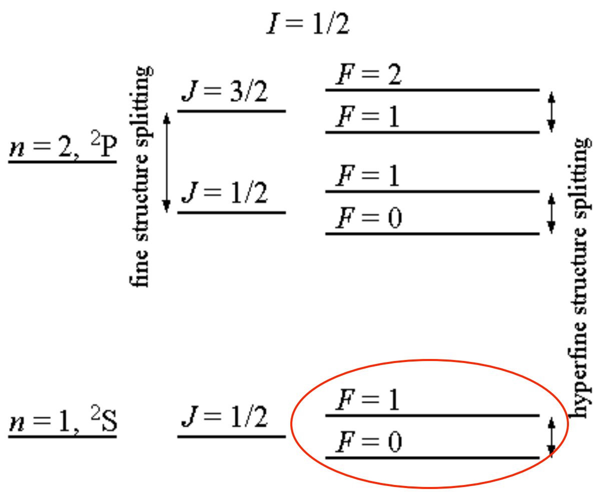
Rayleigh-Jeans tail of thermal emission from e.g. dust grains produces radio emission.

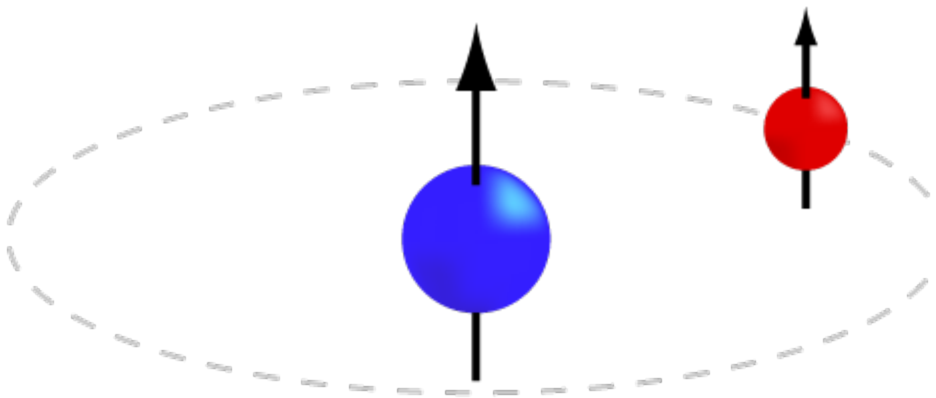


The HI 21cm (1420.4 MHz) Line

Hendrik van der Hulst (1918-2000)

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

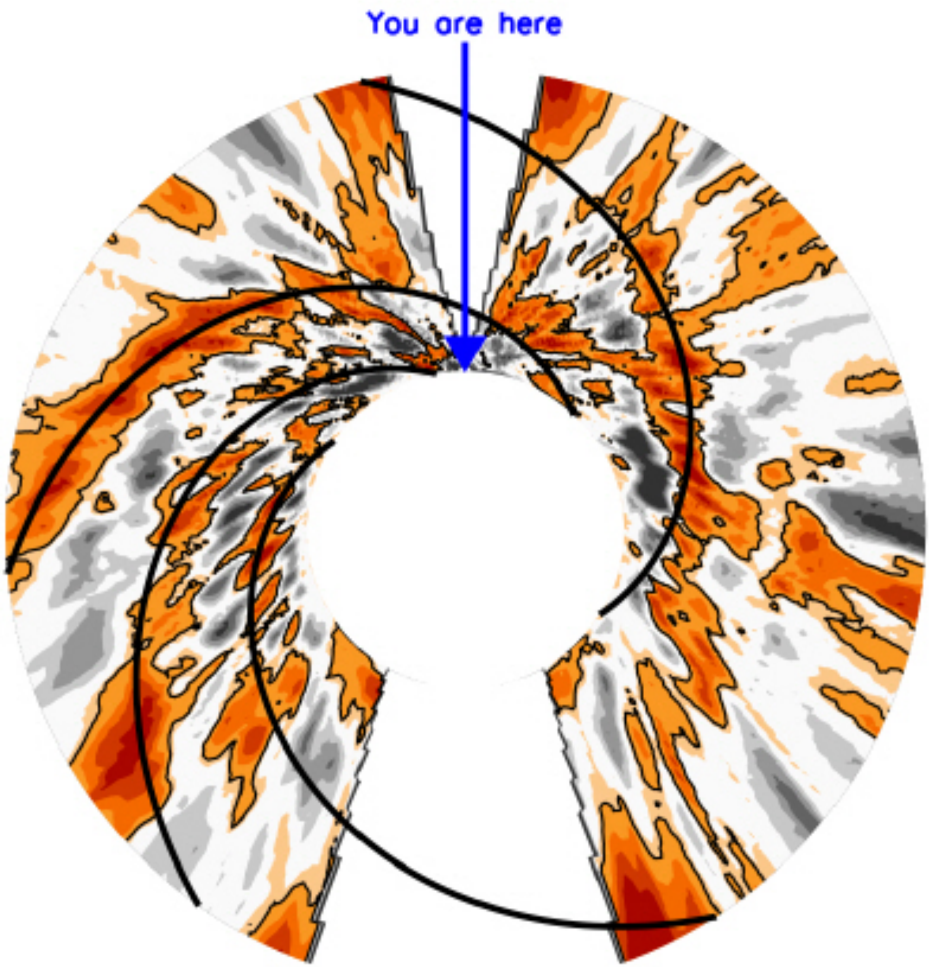




First observed in 1951 by Ewen and Purcell at Harvard University, then by Dutch astronomers Muller and Oort.

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.

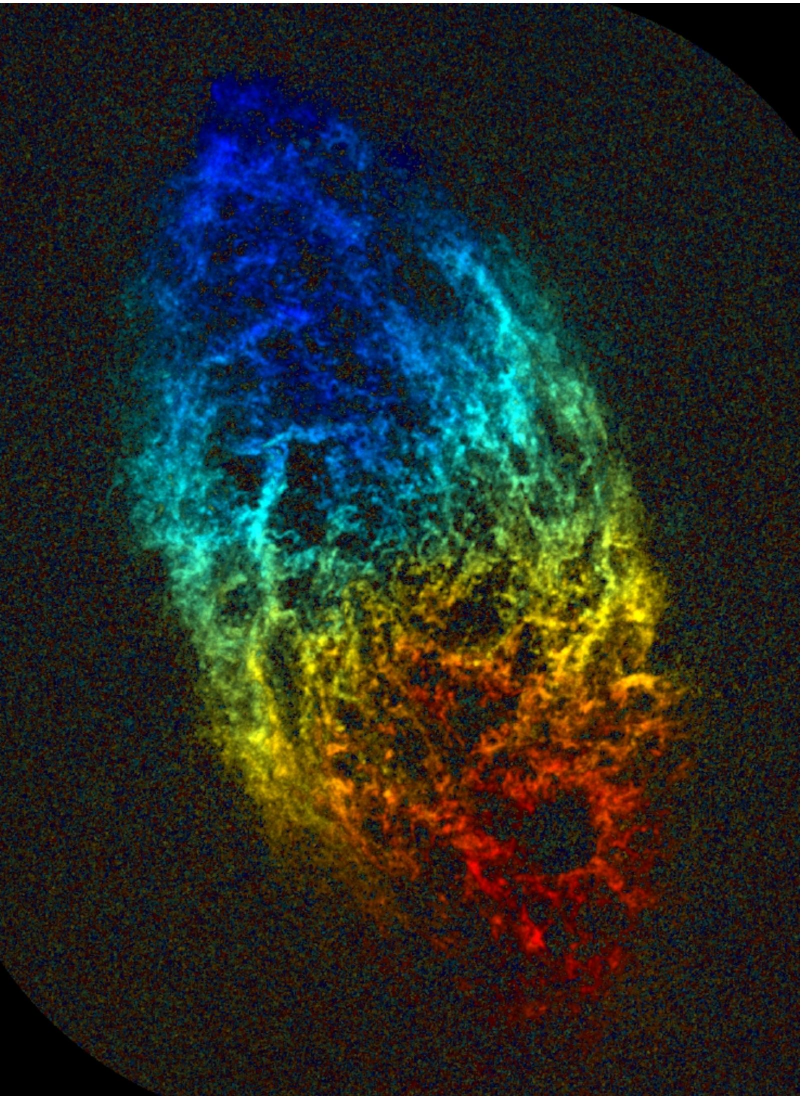
Map of the Milky Way



- Determine location of hydrogen emission from rotational Doppler shift
- Contour plot of hydrogen concentration as seen from the top
- High concentrations in red

http://physicsworld.com/cws/article/news/2006/jun/05/milky-way-arms-pinned-down

Astronomical Relevance of HI 21cm Line



Main applications:

1. Distribution of HI in galaxies
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)***

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 by the interstellar medium (ISM).

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

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

and the relative time delay is:

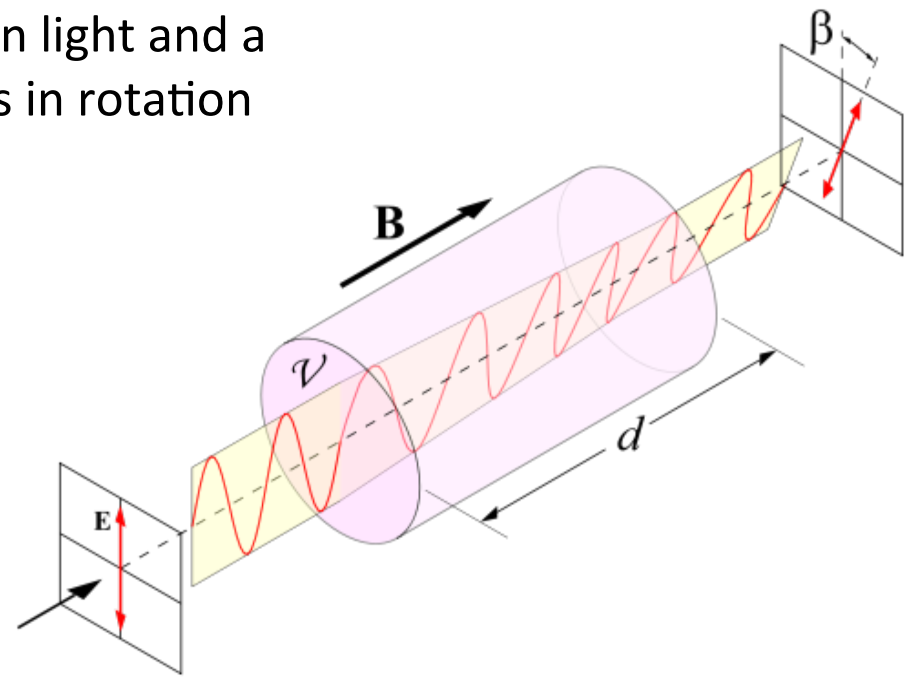
$$\frac{\Delta\tau_D}{\mu s} = 1.34\times10^{-9} \left[\frac{\mathrm{DM}}{\mathrm{cm}^{-2}} \right] \left[\frac{1}{\left(\frac{\nu_1}{\mathrm{MHz}} \right)^2} - \frac{1}{\left(\frac{\nu_2}{\mathrm{MHz}} \right)^2} \right]$$

(lower frequencies are delayed more)

→ good technique to measure either electron densities or distances

Faraday Effect and Rotation Measure

Faraday effect: interaction between light and a magnetic field in a medium; results in rotation of plane of polarization.



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

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

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

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

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

Famous Radio Telescopes (Single Dish)

ALMA: Atacama Large Millimeter Array

Antennae: The Hertz Dipole

- Antennae required to focus power into feed
- Feed is device that efficiently transfers power in the electromagnetic wave to the receiver
- Properties of antennae (beam patterns, efficiencies, …) are the same for transmission and reception.

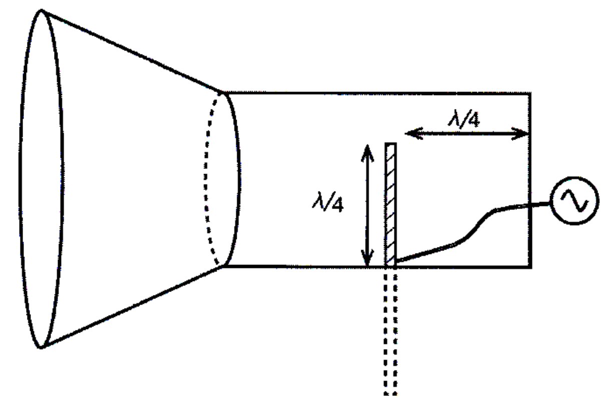
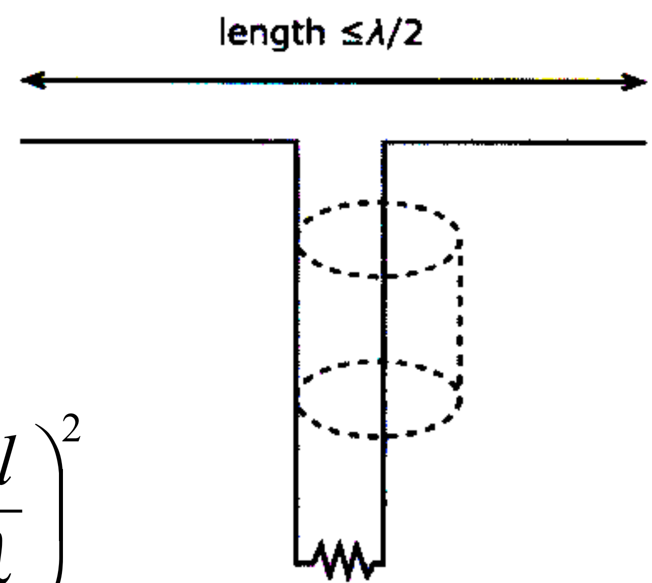


Figure 8.14. A feedhorn with a ground-plane vertical as the antenna. The ground plane vertical creates a full dipole antenna by reflection of one half of such an antenna.

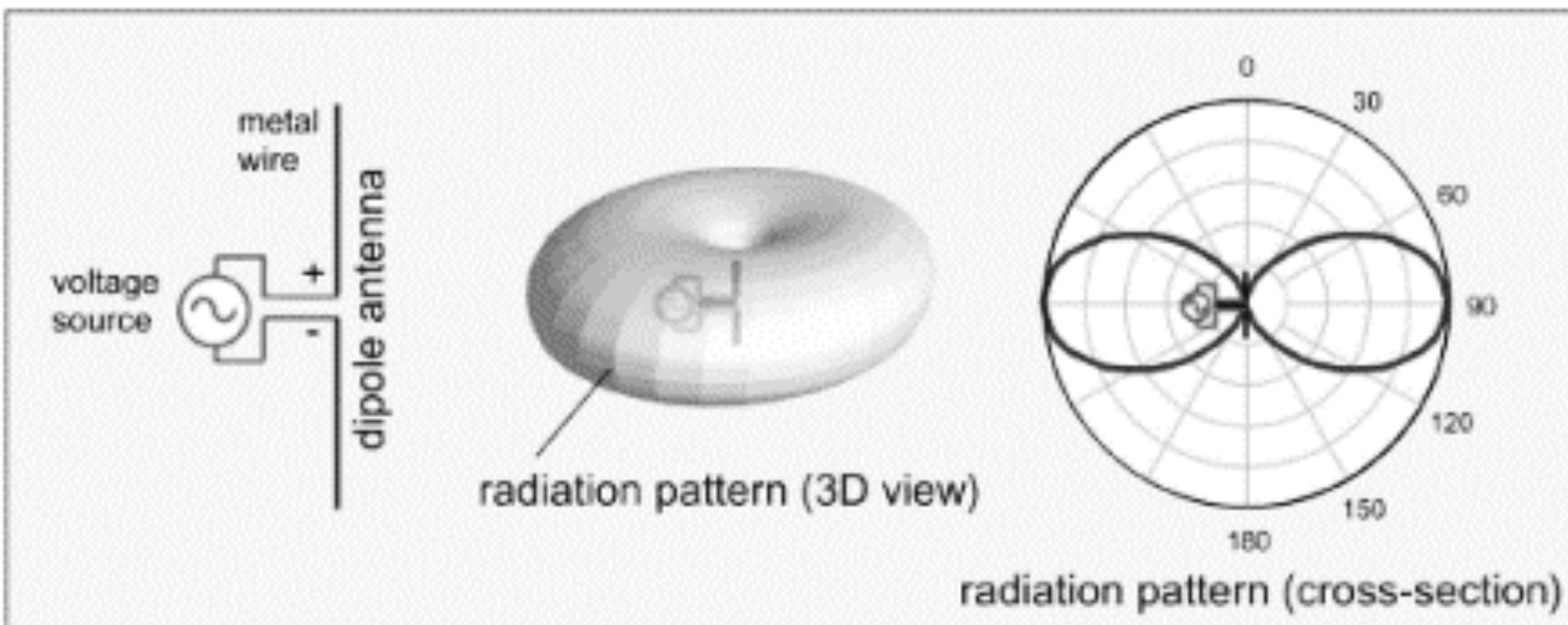
Hertz dipole: total power radiated from Hertz dipole of length Δl carrying an oscillating current *I* at a wavelength λ is:

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



Radiation from Hertz Dipole

- Radiation is linearly polarized
- Electric field lines along direction of dipole
- Radiation pattern has donut shape, defined by zone where phases match sufficiently well to combine constructively
- Along the direction of the dipole, the field is zero
- Best efficiency: size of dipole = 1/2 λ

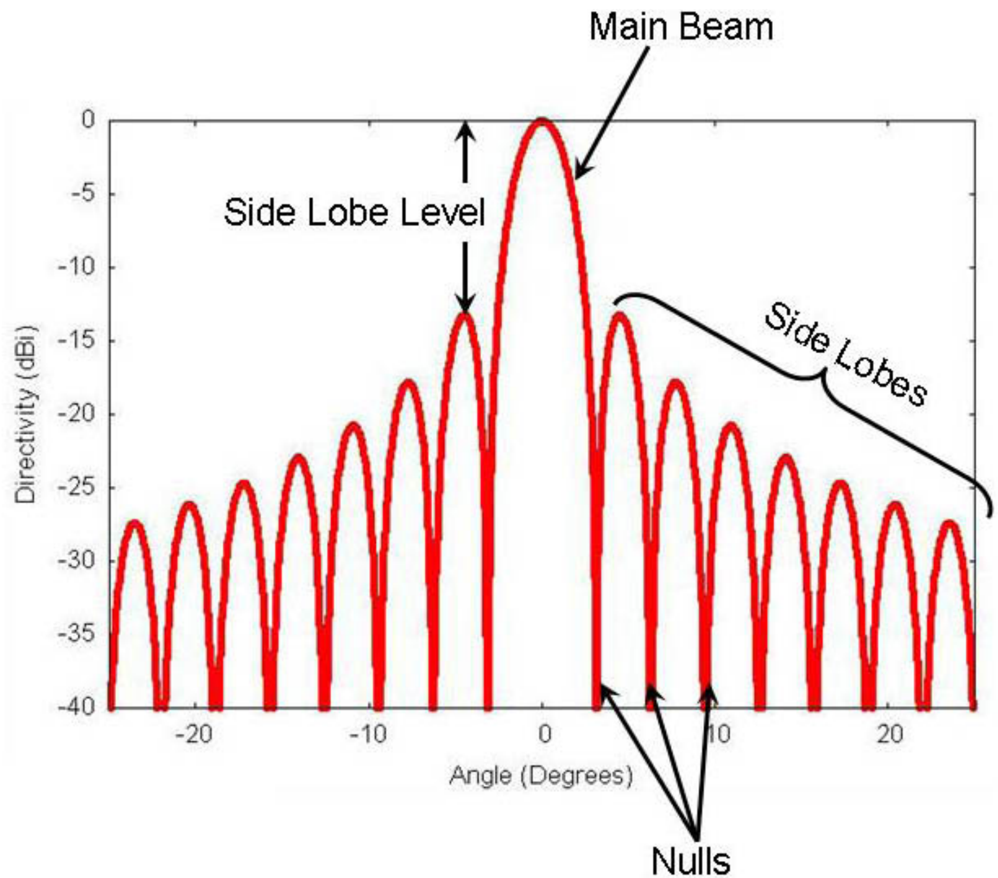


Radio Beams, PSFs and "Lobes"

Similar to optical telescopes, angular resolution given by

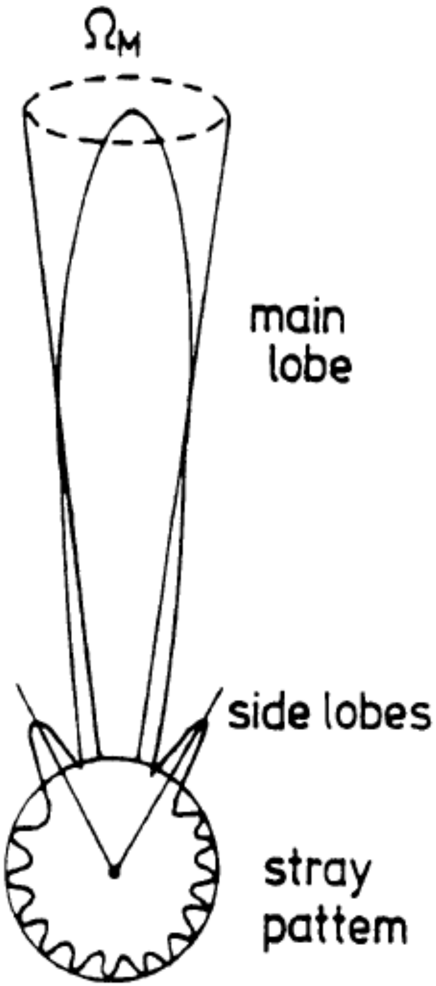
$$\theta = k\frac{\lambda}{D}$$ where k ~1.

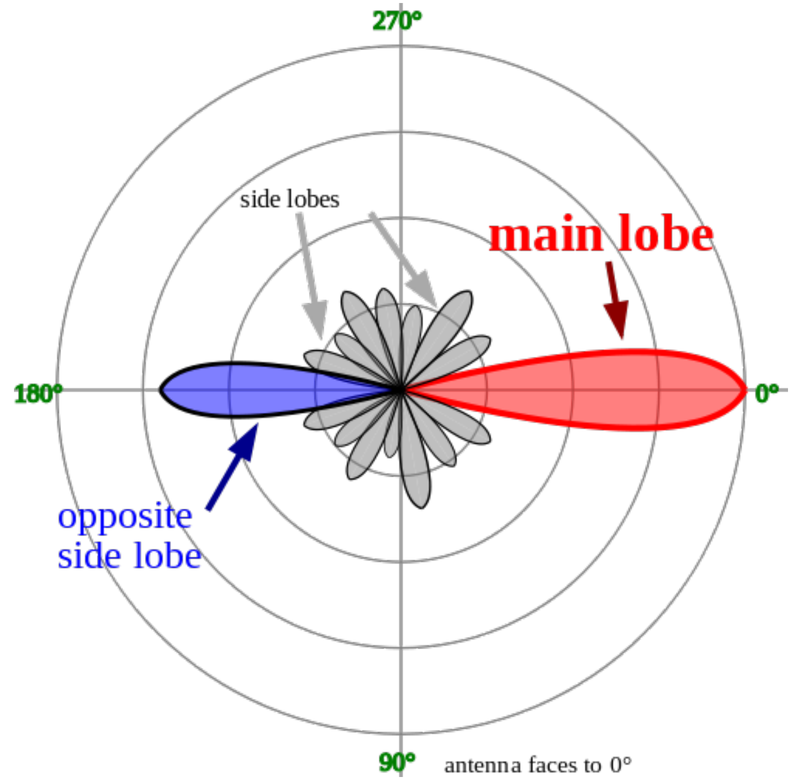
Radio beams show – just like the Airy patterns of optical PSFs – patterns of "lobes" at various angles, directions where the radiated signal strength reaches a maximum, separated by "nulls", angles at which the radiated signal strength falls to zero.



Main Beam and Sidelobes

Highest field strength in "main lobe", other lobes are called "sidelobes" (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 Ω_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 Ω_A for an ideal antenna.

Main beam solid angle Ω_{MB} is:

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

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

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

Coherent (Heterodyne) Receivers

Problems with detecting and amplifying signals (electromagnetic waves):

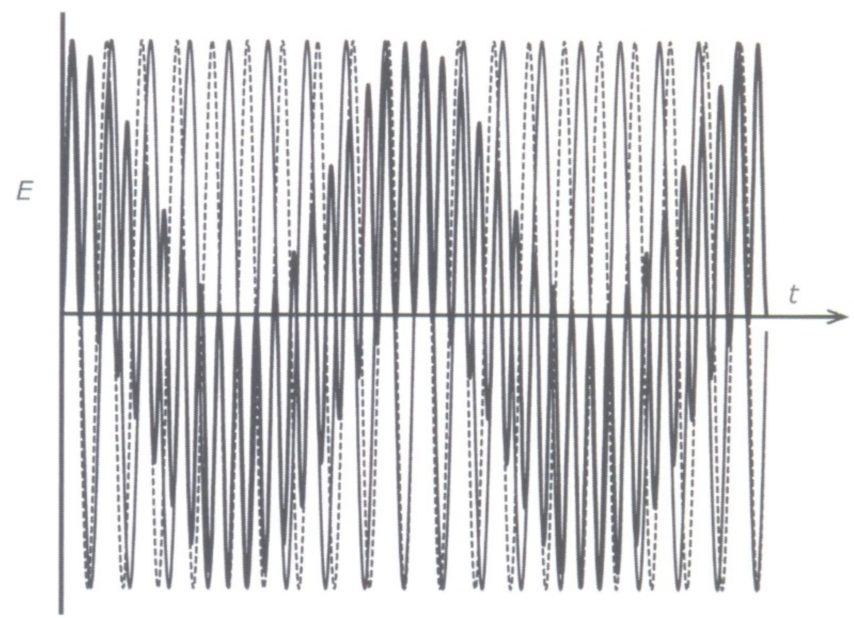
1. The signals are usually very weak
2. The frequencies are too high for standard electronics

$\lambda = 1\ \mu m \Leftrightarrow \nu = 300\ THz \Leftrightarrow \Delta t = 3.3 \cdot 10^{-15}\ s$

$\lambda = 100\ \mu m \Leftrightarrow \nu = 3\ THz \Leftrightarrow \Delta t = 3.3 \cdot 10^{-13}\ s$

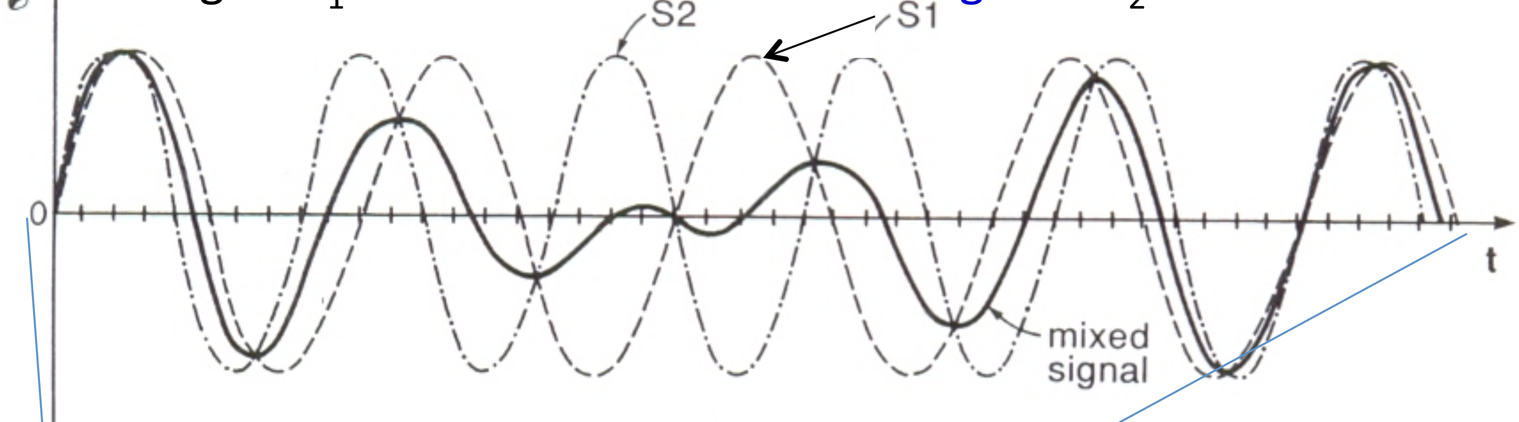
$\lambda = 1\ cm \Leftrightarrow \nu = 30\ GHz \Leftrightarrow \Delta t = 33\ ps$

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

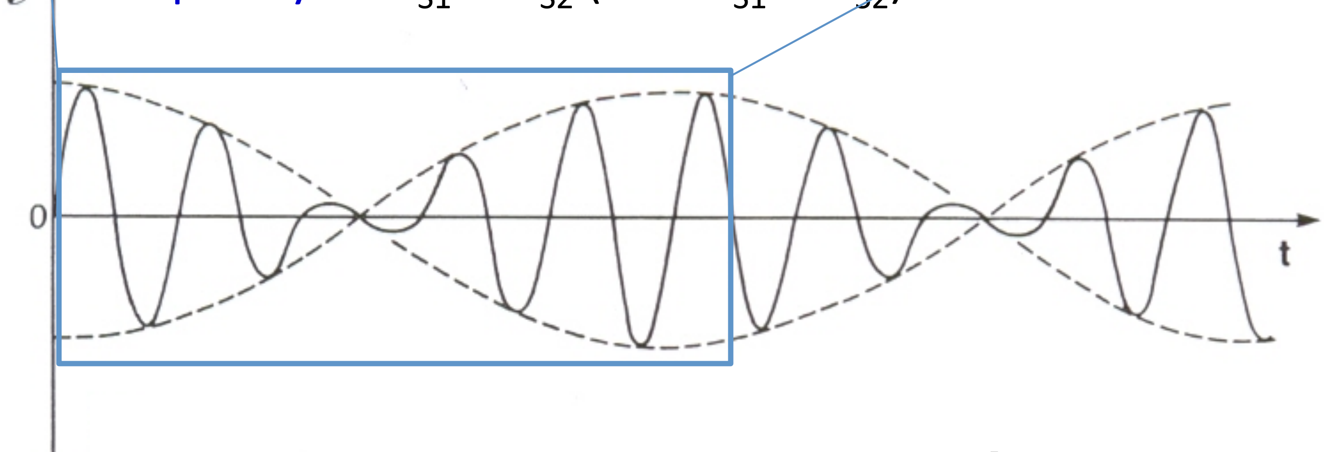


Principle of Frequency Mixing

1. Signal S_1 is mixed with local oscillating field S_2



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



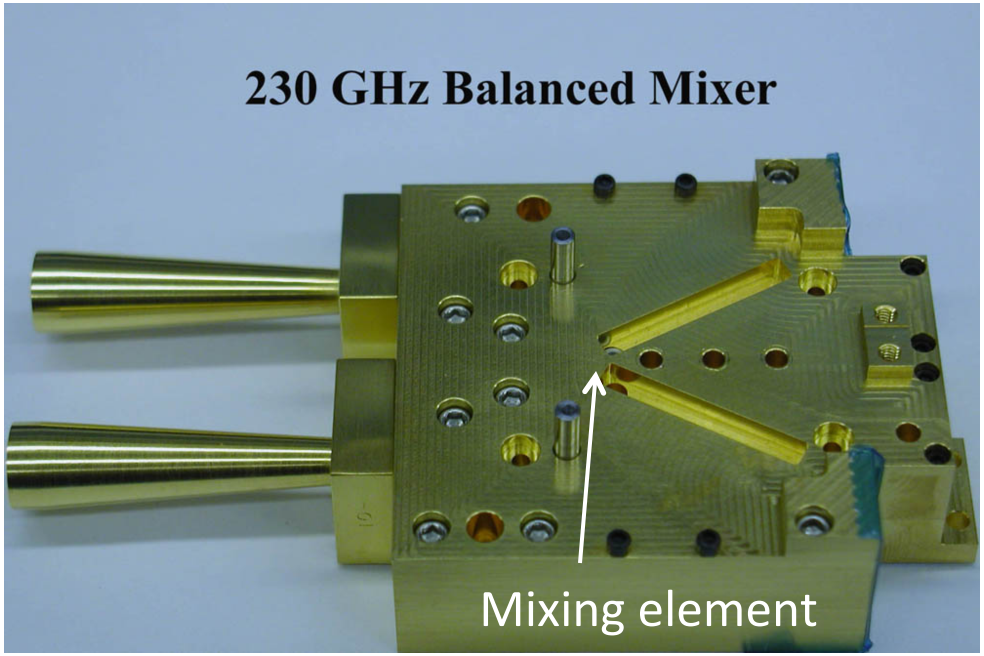
- encodes signal over a wide wavelength range → ideal for spectroscopy
- typically, power(ω_{LO}) » power(ω_S) → amplification by oscillator signal
- down-conversion to frequencies where low-noise electronics exist

Mixer Technology

Example of a mixer:

Source signal →

Local oscillator signal →

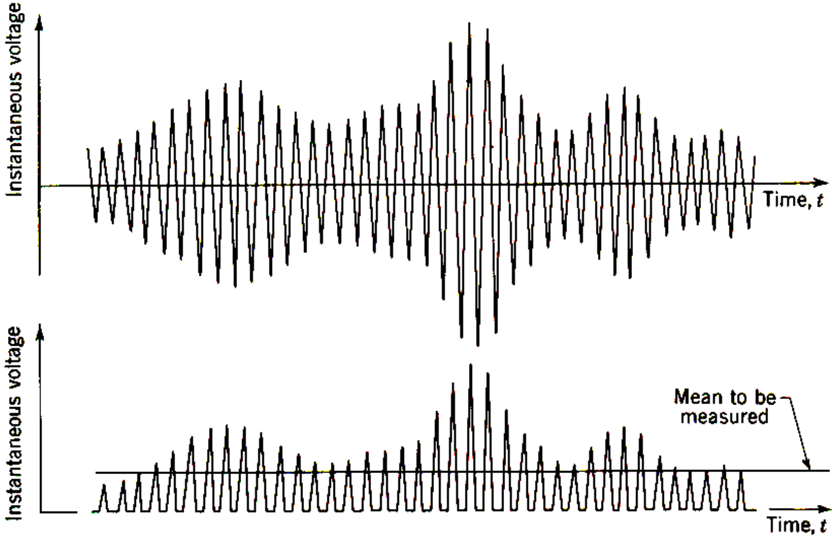


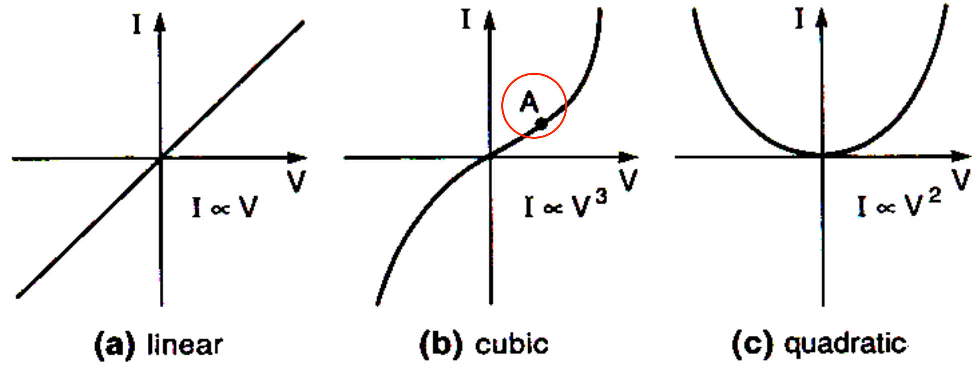
Problem: good & fast "traditional" photo-conductors do not exist for $\nu < 7.5$ THz

➔

- Schottky diodes
- SIS junctions
- Hot electron bolometers

Mixer Output

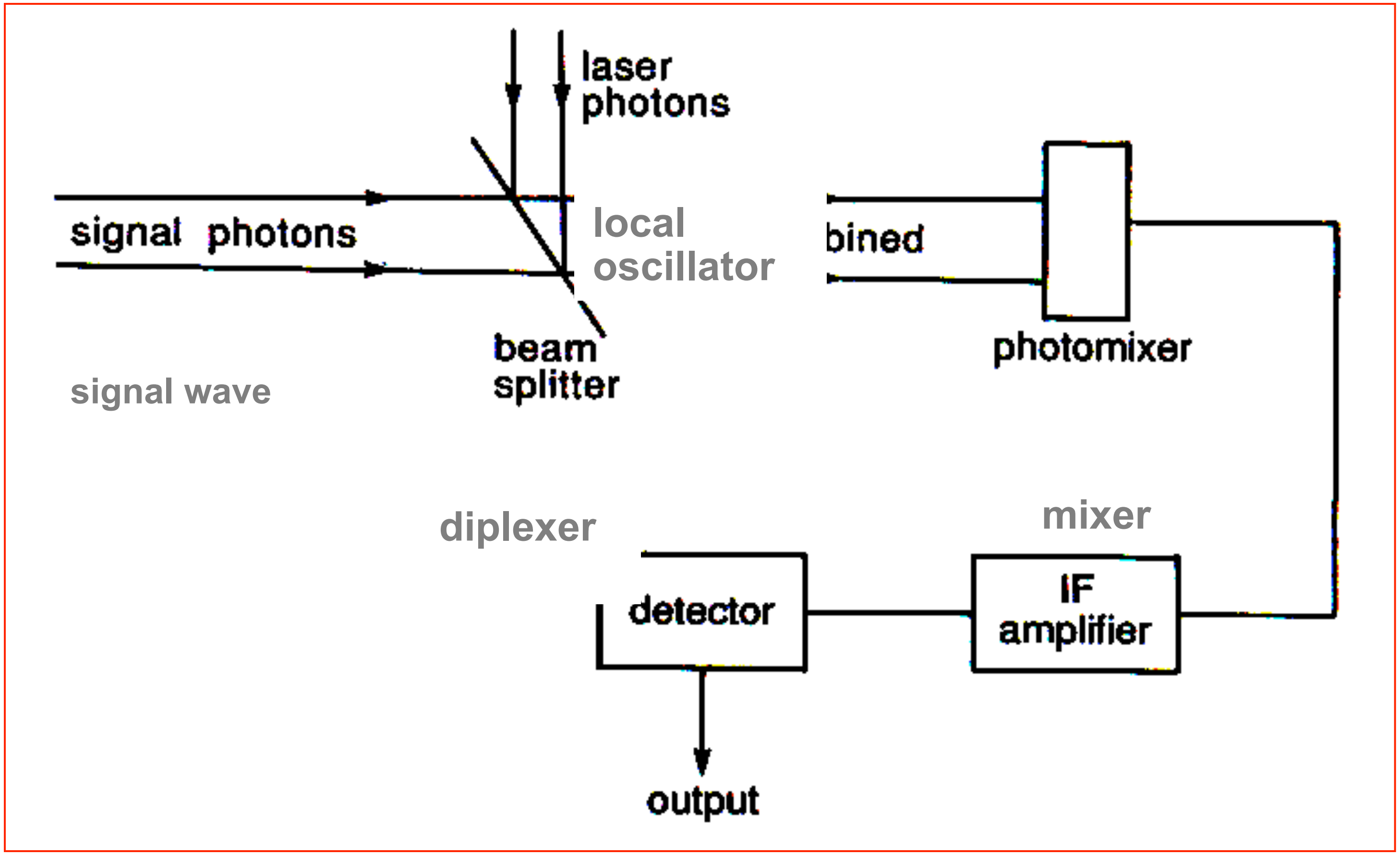




- linear device (a) yields no output power at any frequency.
- non-linear device (b,c) can convert power from the original frequencies to the beat frequency
- even if the mixer has an odd function of voltage around the origin (b) the conversion efficiency is zero.
- but if biased above zero (**A**) the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

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

Basic Heterodyne System



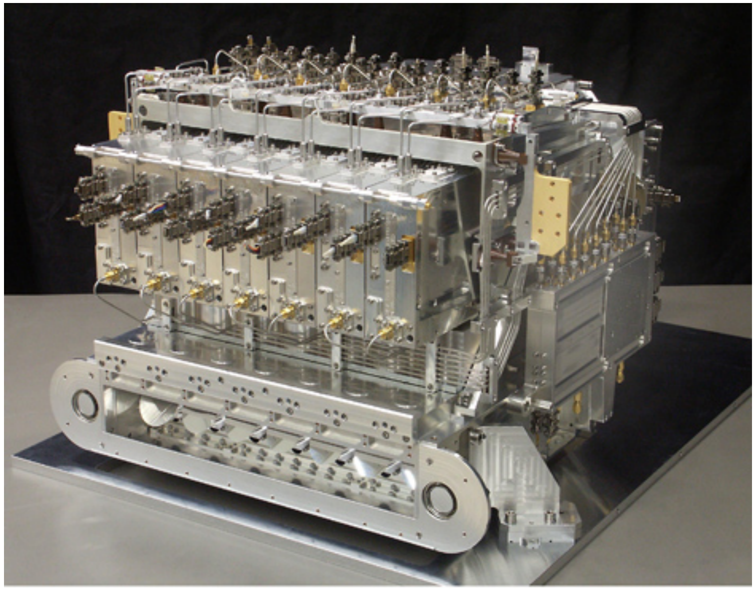
"Back End" specifies the devices following the IF amplifiers. Many different back ends have been designed for specialized purposes such as continuum, spectral or polarization measurements.

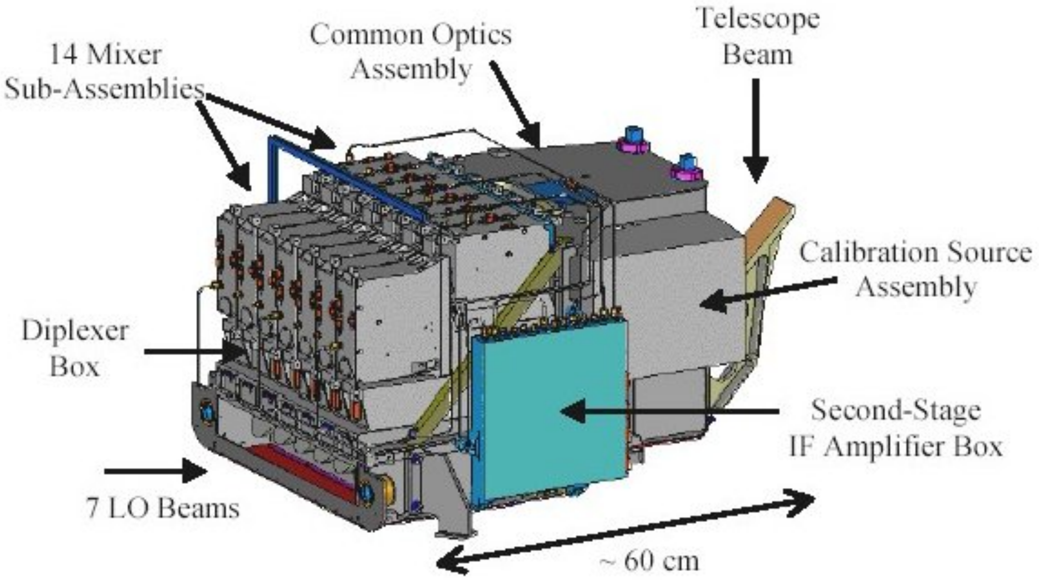
Polarimeters

Antennas with fixed-dipole feeders or horn feeders 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.

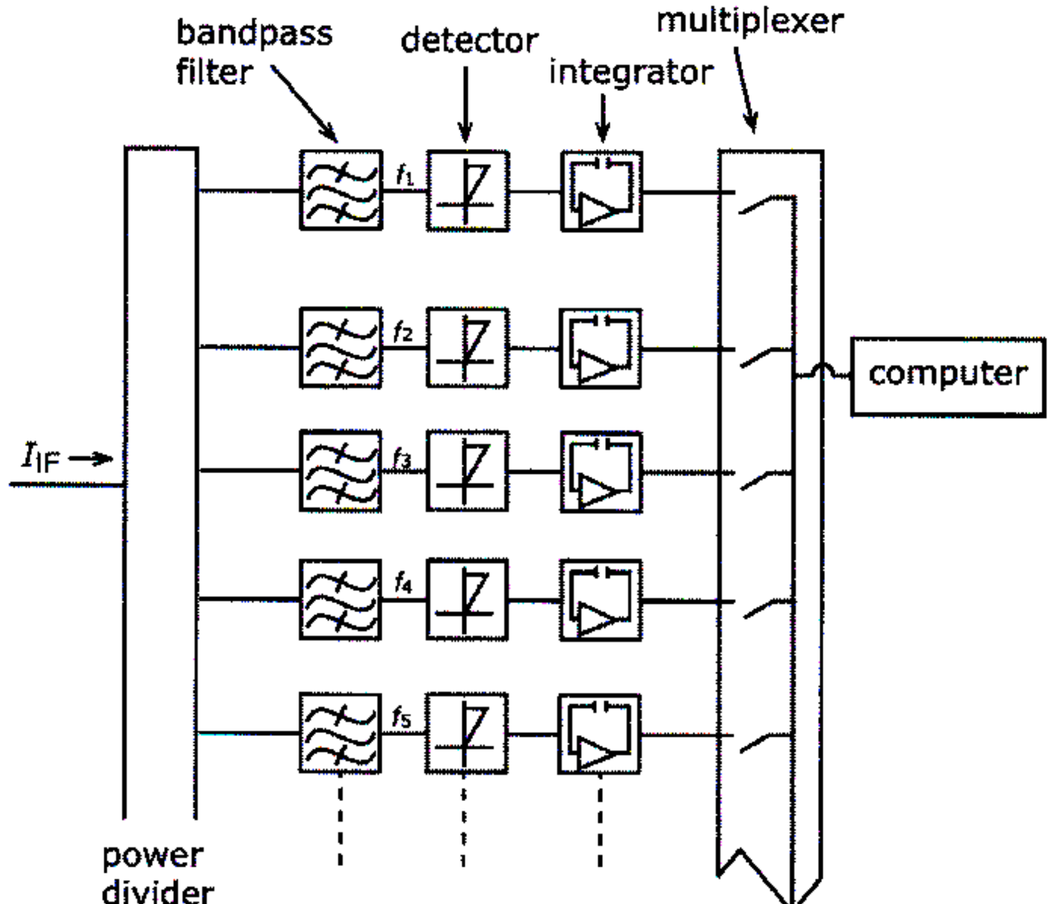
Heterodyne dual polarization receiver = two identical systems, connected to the same local oscillator, and sensitive to only one of the two orthogonal polarizations. Can provide values of all polarization parameters simultaneously.





Multichannel Spectrometer

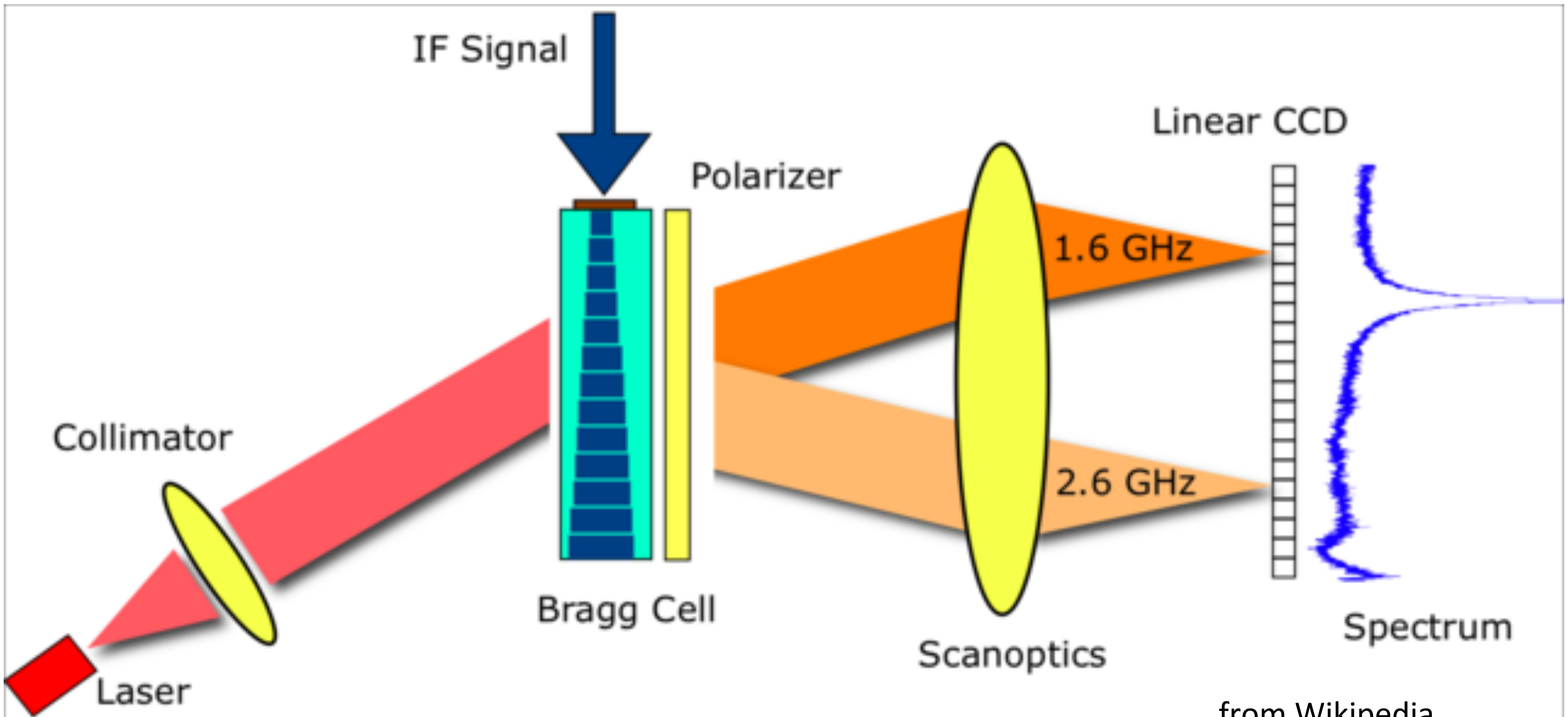
The IF input signal is divided among the bandpass filters ("filter bank") and the output of each is processed by a detector/integrator stage. The outputs of these stages are switched sequentially to the computer where the spectrum can be displayed.



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

Acousto-Optical Spectrometer (AOS)

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



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

Autocorrelation Spectrometer

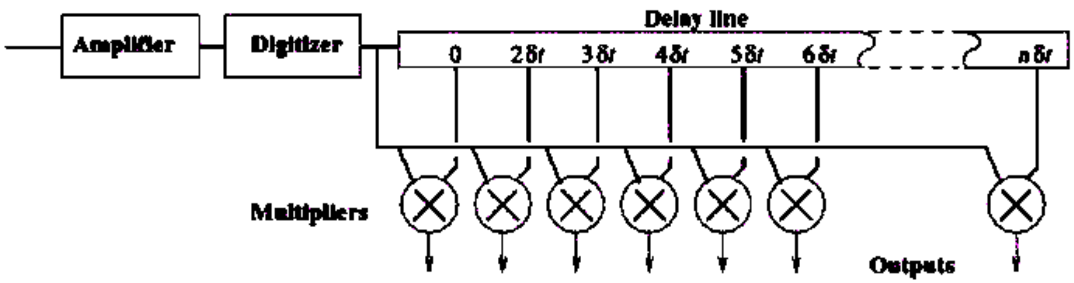
Reminder:

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

1. Given: time dependent IF signal f(x)
2. Want: Power spectrum I(ν) = |f(s)|^2
3. |f(s)|^2 could 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



“True” Brightness Temperature

- Rayleigh-Jeans approximation:

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

- brightness and effective temperature are strictly proportional
- Can use brightness temperature to describe source intensity:

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

- Note: usually only fulfilled if source fills beam (very extended sources)
- If the source is a real black body *hν* << kT, then T_B is independent of *ν*
- If the emission is non-BB (e.g., synchrotron, free-free, …) T_B will depend on *ν* but the brightness temperature is still being used

Main Beam Brightness Temperature

Relation between flux density S_ν and intensity I_ν:

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

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:

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

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

$$\theta^2_{observed} = \theta^2_{source} + \theta^2_{beam}$$

…which relates the true brightness temperature with the main beam brightness temperature:

$$T_{MB}\left(\theta^2_{source} + \theta^2_{beam}\right) = T_B \, \theta^2_{source}$$

Noise Temperature

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

$$P_\nu = kT$$

…and is also called the 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

Noise temperature (receiver temperature) can be measured by comparing the signals of two artificial sources with effective temperatures T_1 and T_2. The total power is given by:

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

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

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:

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

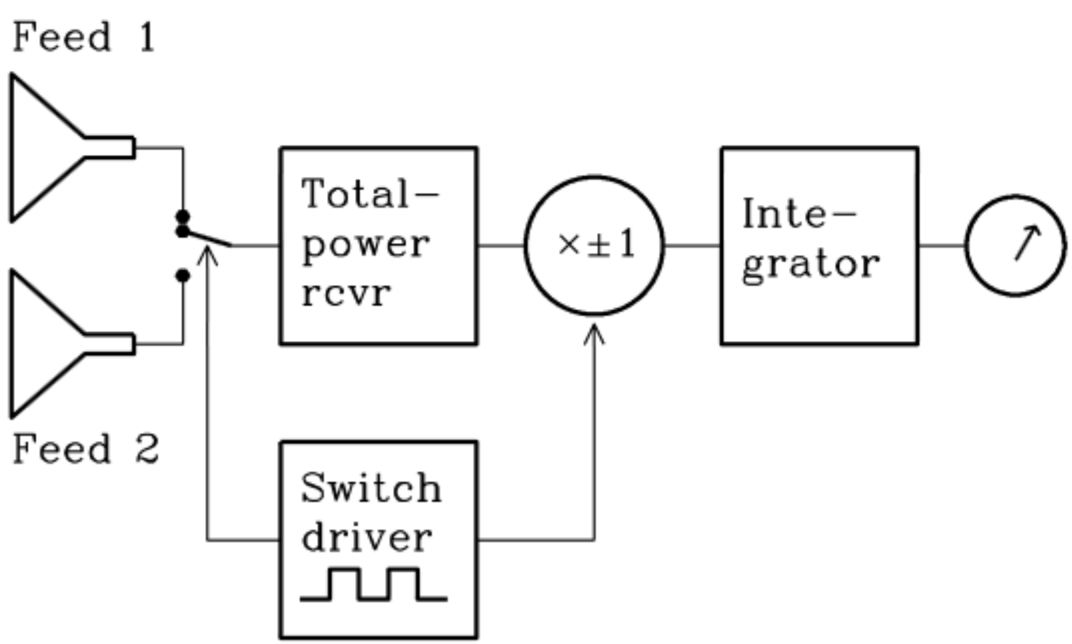
Receiver Stability and Dicke Switching

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

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

Disadvantage: 50% of total time is spent to look at flux reference.

Robert Henry Dicke
(1916-1997)



Spectral Line Observations

Three common observing modes to detect weak spectral lines:

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 ~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.