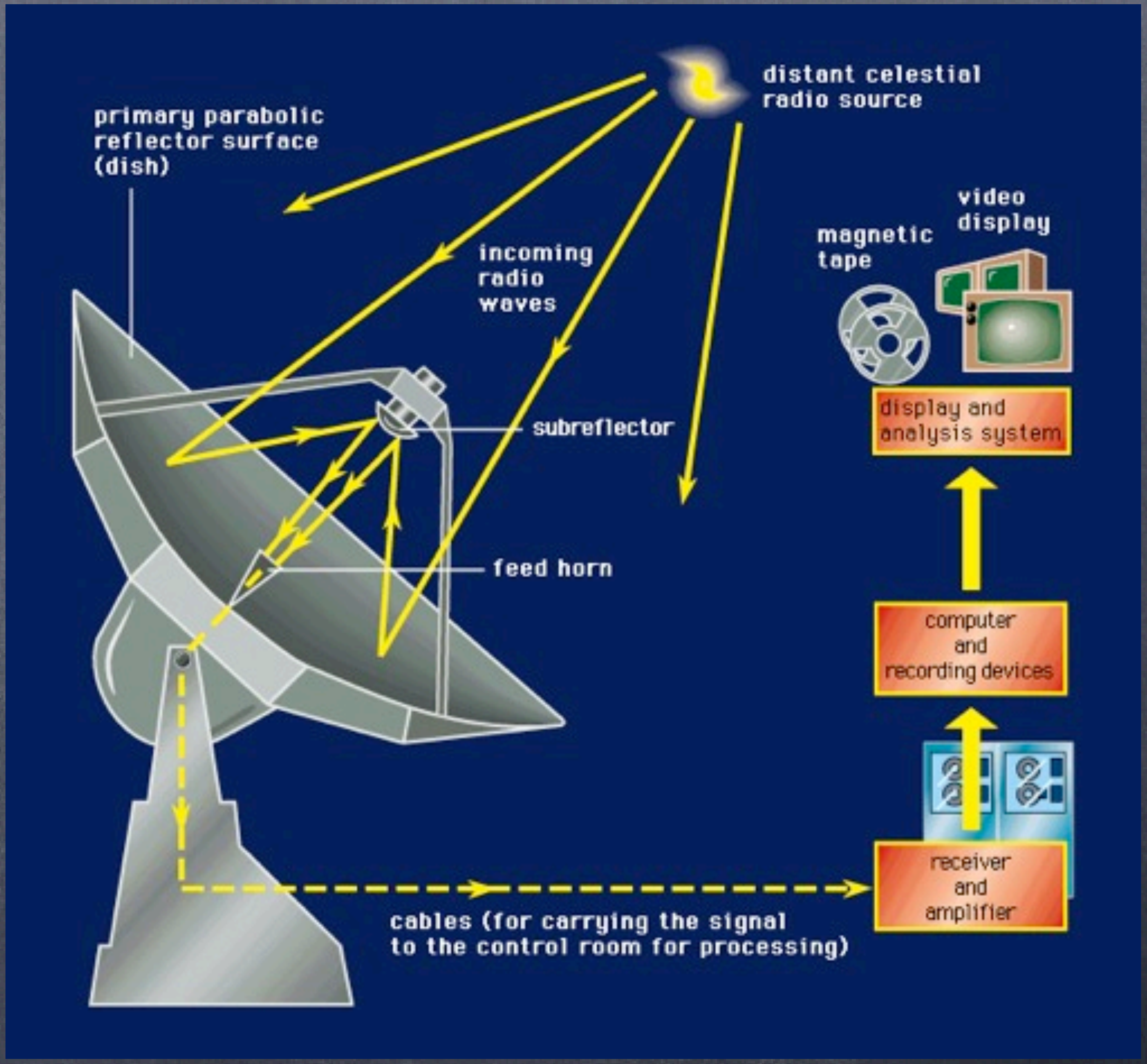
More Radio Astronomy

Radio Telescopes - Basic Design

A radio telescope is composed of:

- a radio reflector (the dish)
- an antenna referred to as the feed on to which the radiation is focused
- a radio receiver

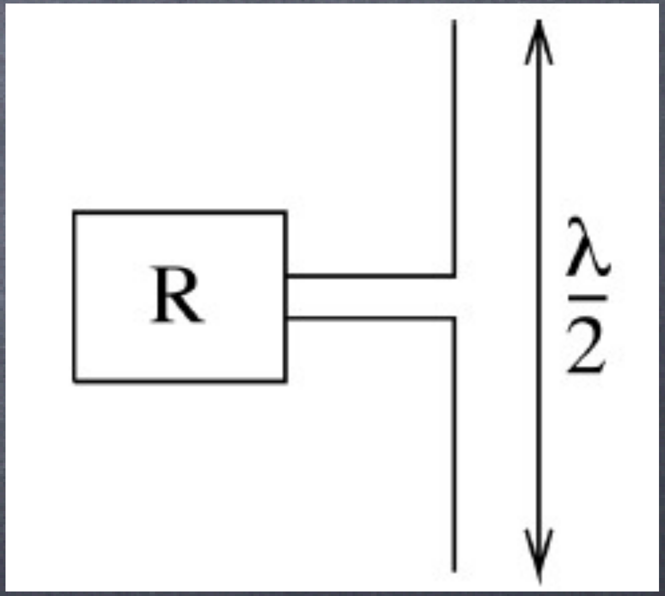


Antennas - The Feed

Receiving antenna's convert electromagnetic radiation to an electrical current (or vice-versa for a transmitting antenna).

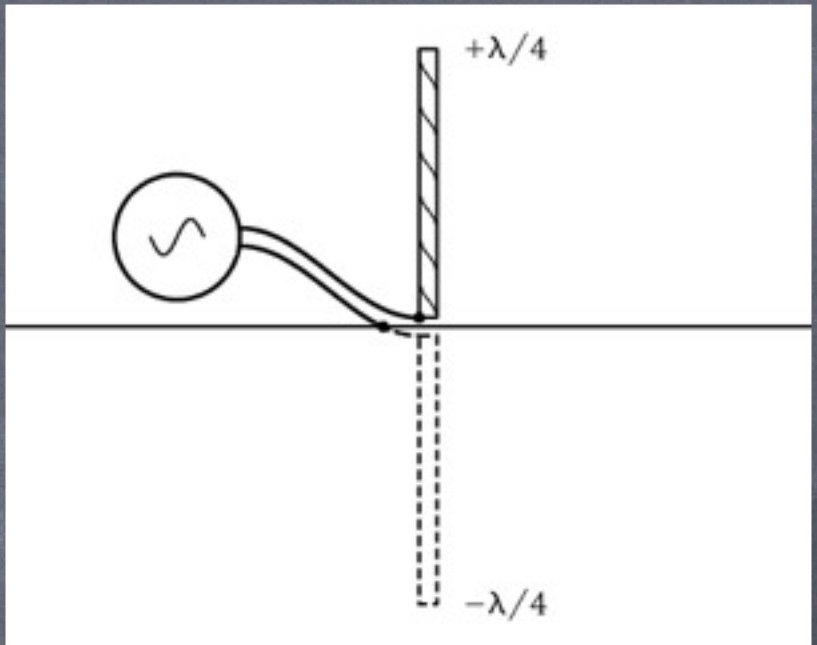
In radio telescopes, the large parabolic reflector focuses radiation to a feed antenna.

The simplest antenna is the half wave dipole consisting of two conducting wires with length 1/4 of the wavelength. The electric field of incoming radio waves induces an oscillating current which can be measured.

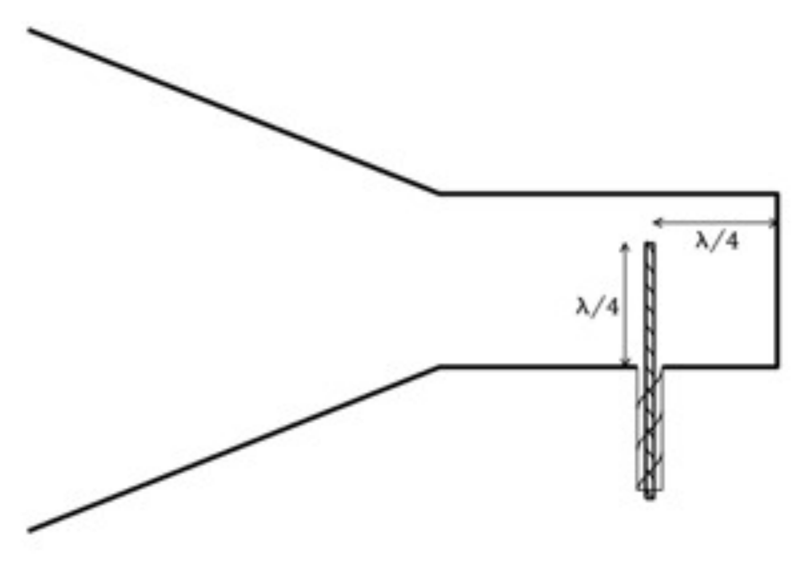


Antennas - The Feed

A close relative of the half wave dipole is the ground plane vertical, which is one half of the dipole above a conducting plane. The conducting plane mirrors the vertical such that the horizontal electric field is zero on the conductor.



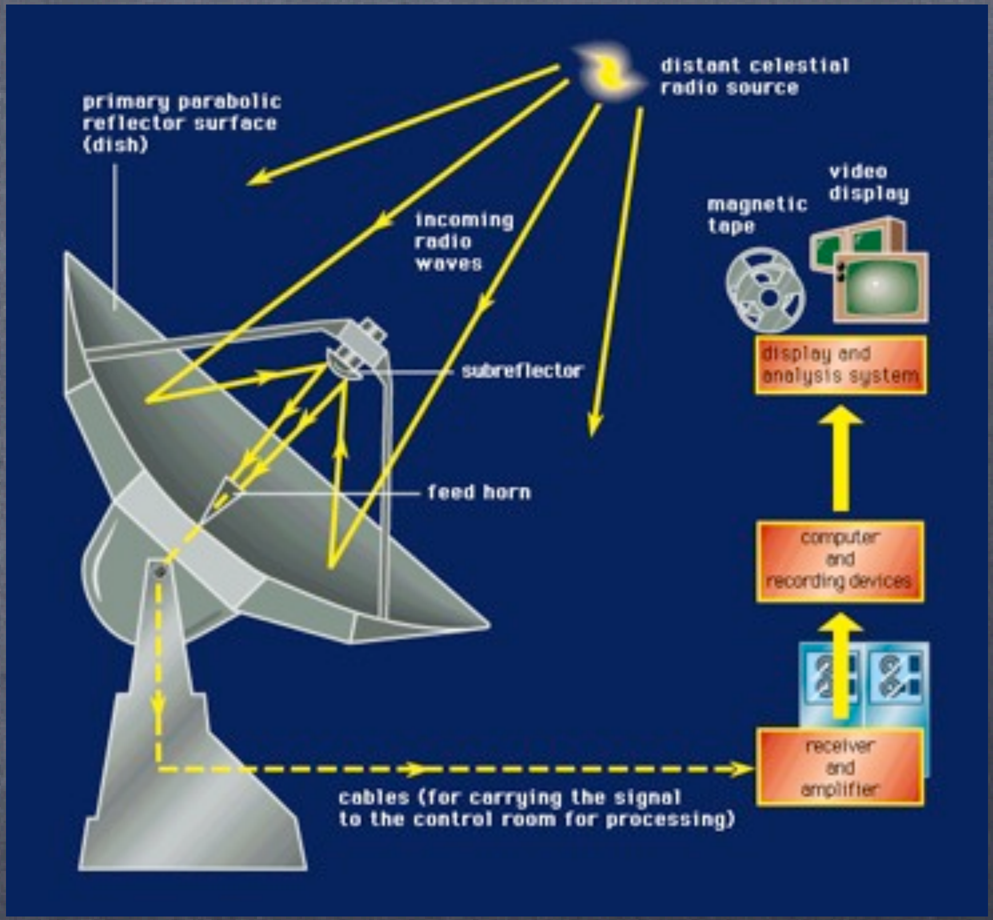
The feeds in many radio telescopes are quarter wave ground plane verticals inside a waveguide horn. In the waveguide horn radiation enters the tapered horn and is concentrated into the waveguide with parallel conducting walls.



"ESSENTIAL RADIO ASTRONOMY", Condon and Ransom

Feed Antennas

The VLA, photo by J. Condon



Noise Temperature

In radio astronomy, noise sources are typically listed in terms of temperature. The noise power is compared to a resistor at a temperature T whose thermal noise would produce the same power per unit bandwidth as the source.

Nyquist formula: In the limit of $h\nu \ll kT$ the noise power per unit bandwidth of a resistive element at a temperature T is

$$P_\nu = kT$$

Thus the noise temperature is $T_N = P_\nu/k$

Receiver temperature: The receiver itself with no input signal generates noise which is the receiver temperature. Receiver noise is usually minimized by cooling the receiver to cryogenic temperatures.

Antenna Temperature

Unit for the power output per unit frequency of a receiving antenna. It is the temperature of a resistor whose thermal power per unit frequency would be the same as that produced by the antenna.

$$T_A = P_\nu/k$$

$T_A = 1$ K corresponds to $P = kT_A = 1.38\text{x}10^{-23}$ W Hz^{-1}

A source with a flux density S increases the antenna temperature by

$$T_A = A_* S/2k$$

where A is the effective collecting area. It can be calibrated by comparison to hot and cold loads (i.e. resistors).

System Noise

The system noise temperature is the total noise power from all sources. It is the sum of many contributions.

$$T_{\rm sys} = T_{\rm cmb} + \Delta T_{\rm source} + T_{\rm atm} + T_{\rm spillover} + T_{\rm rcvr} + \ldots$$

noise from CMB

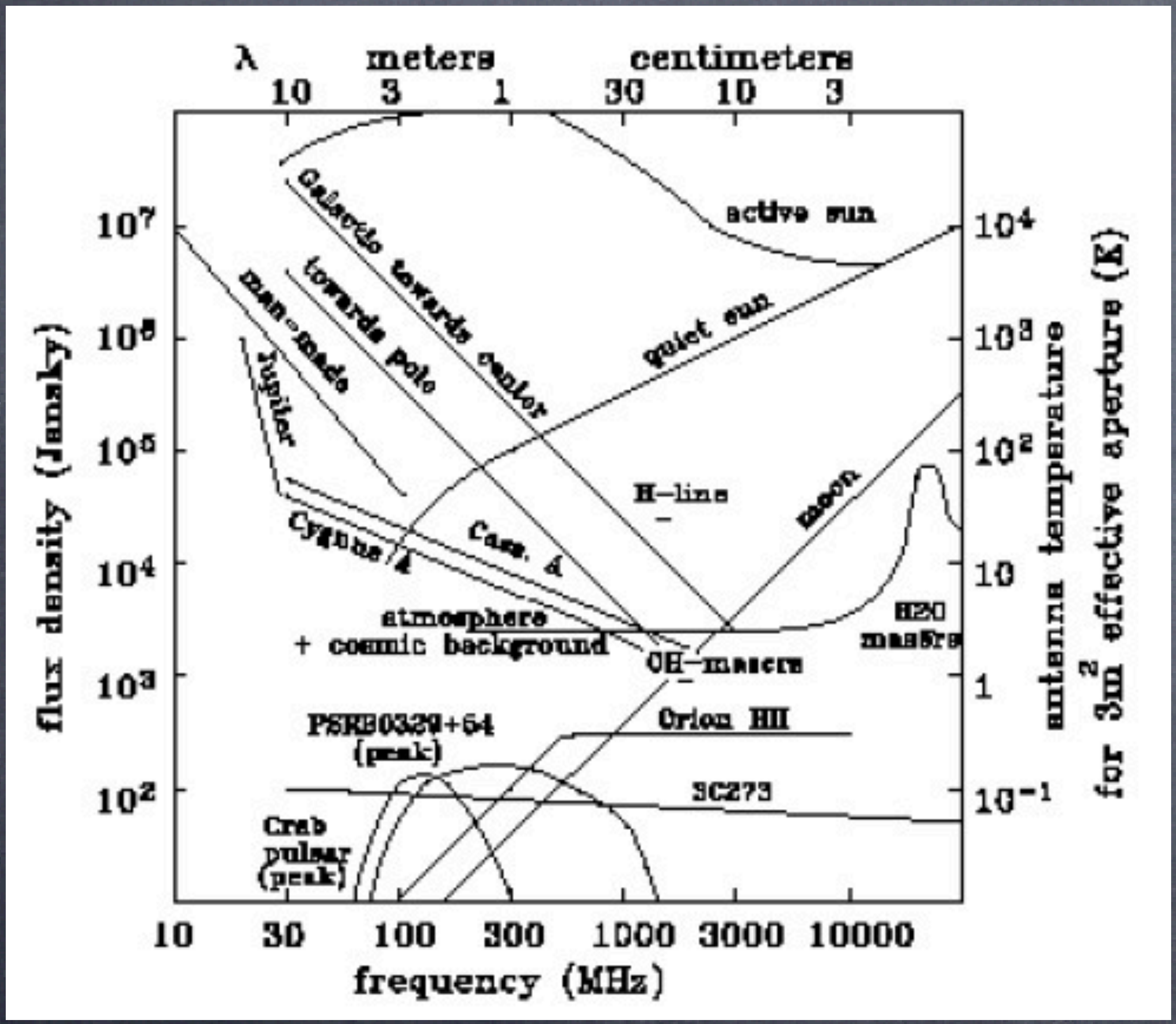
noise from source

atmosphere

spillover

receiver, minimized by cryogenic cooling

System Noise Contributions



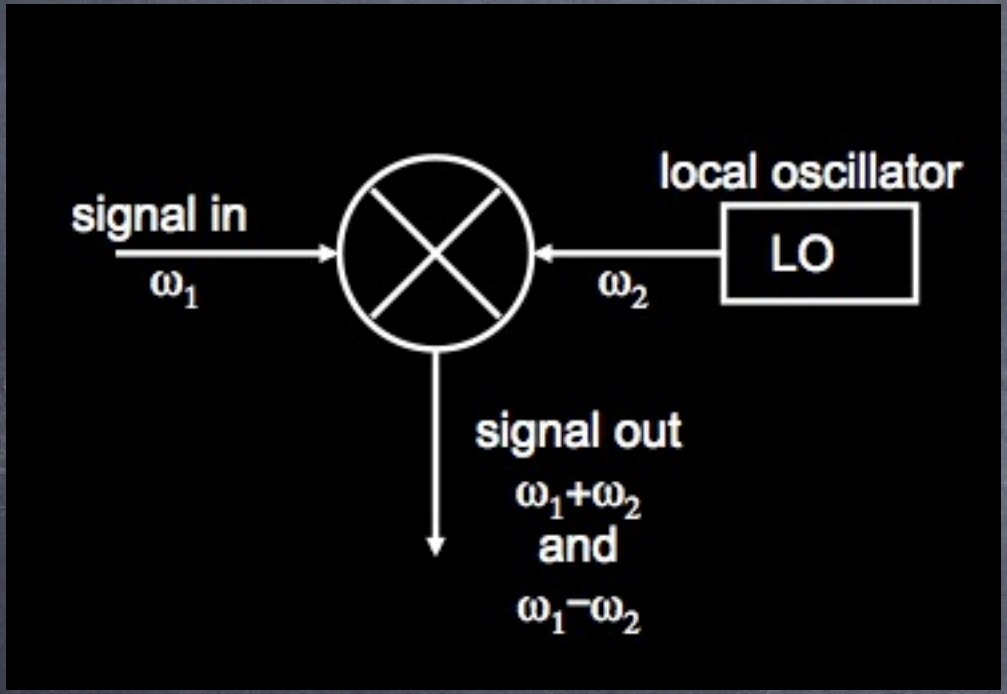
Radio Astronomy Tutorial - Haystack Observatory

Lowest system noise is on the order of 20 K around 1.4 GHz

At lower frequencies (400 MHz), galactic noise is significant (50-100 K).

Radio Receivers

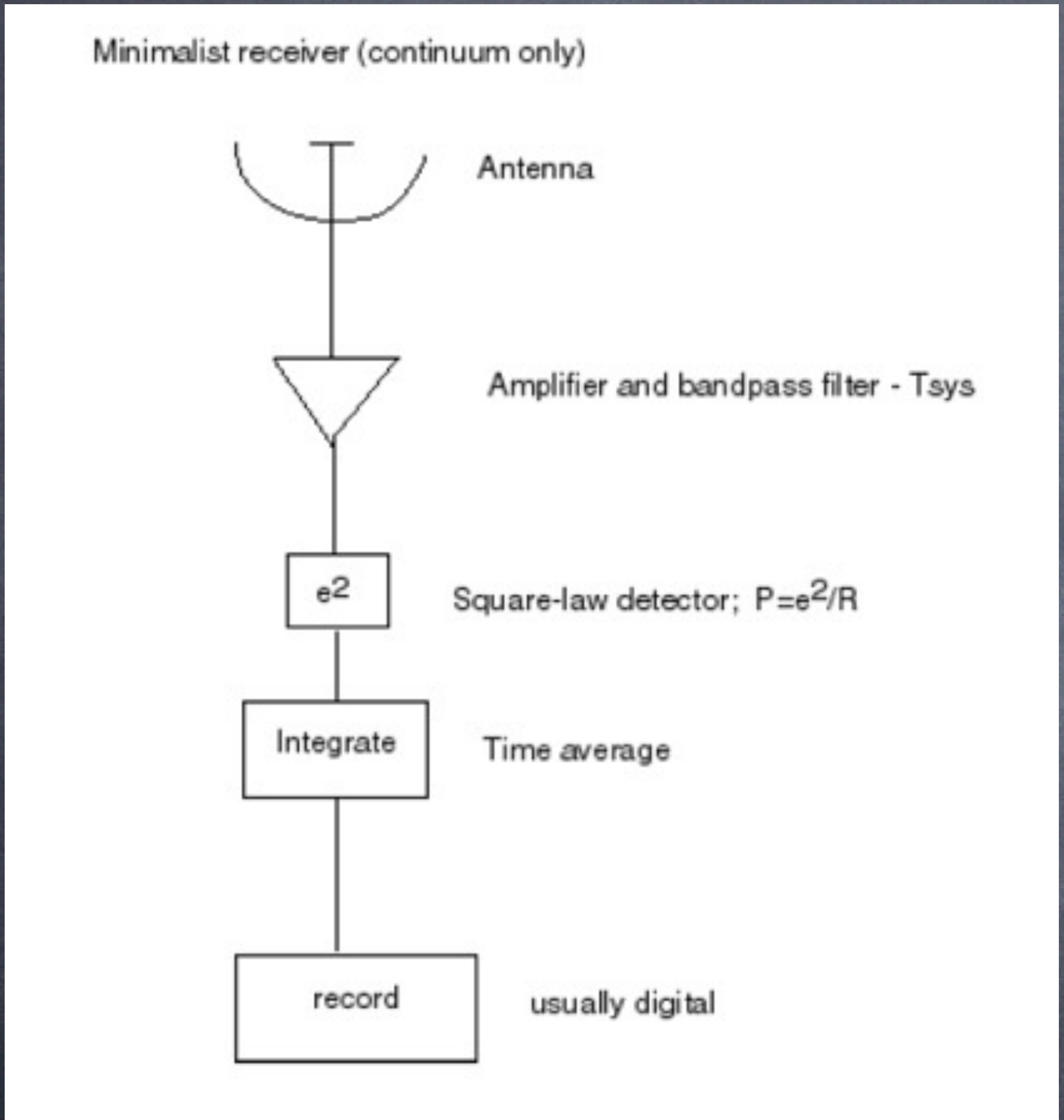
Heterodyne receivers: shift the frequency of incoming radiation through mixing with a stable second frequency making it easier to measure. Coherent receivers in that they preserve phase.



Element referred to as a mixer. Outputs the sum and difference of the frequencies, and usually filter out the higher frequency. LO can be tuned to control output frequency.

Bolometers: Material whose resistance changes with temperature. Used for shorter wavelength observations. Not sensitive to frequency or polarization.

Simple Radiometer



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Consists of four stages:

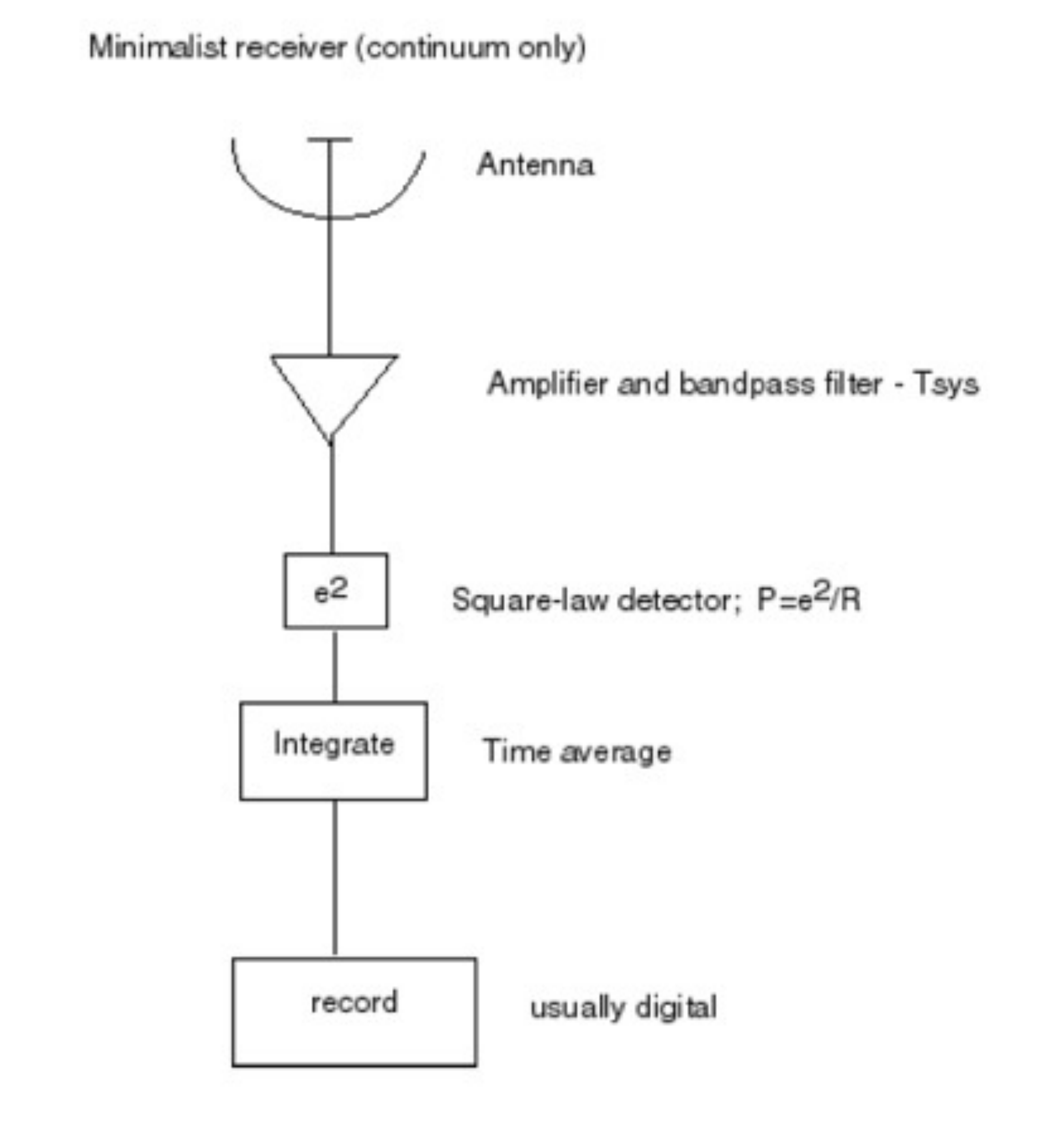
(1) an bandpass filter and amplifier

(2) an square-law detector

(3) a signal averager or integrator that smoothes out output

(4) a voltmeter or other device to measure the output

Simple Radiometer



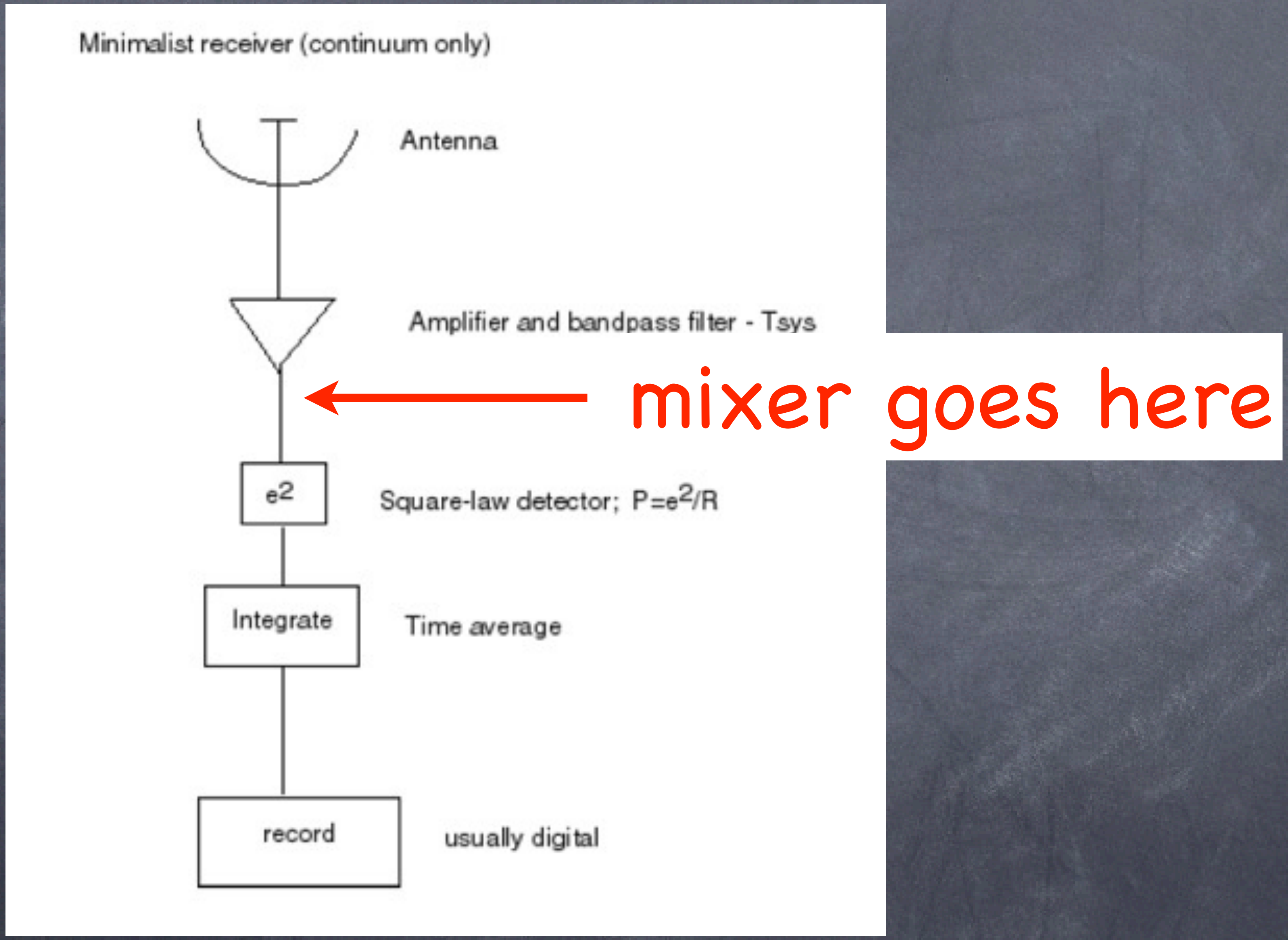
Radio Astronomy Tutorial - Haystack Observatory

Radio signals are typically very weak, so amplifiers are used to increase the signal. These amplifiers must be very low noise, and are often cooled.

The amplifier is followed by a square-law detector, whose output voltage is proportional to the square of the input voltage (i.e. translates voltage from the antenna to power).

The signal is then passed to an integrator, which averages the signal over some amount of time.

Radio Receivers



Detection Limit

The error on the system temperature is something like:

$$\sigma \approx T_{sys}/\sqrt{(\Delta\nu * t)}$$

where $\Delta\nu$ is the bandwidth and t is the integration time. The denominator gives essentially the number of measurements which get averaged.

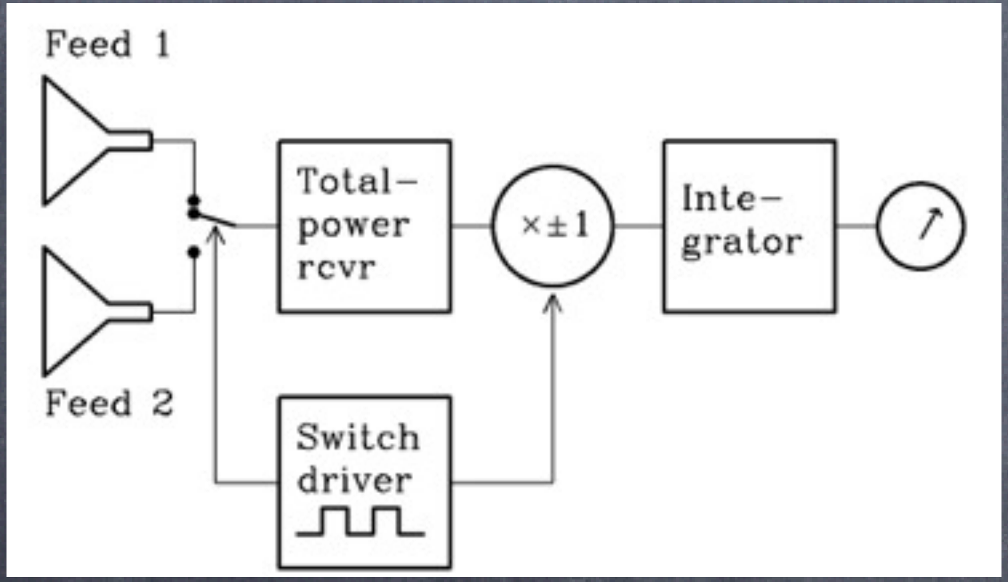
$\Delta\nu * t = 10^8$ would not be unusual. Taking 5σ for a detection means you can detect sources with

$$T \approx 5\times10^{-4}\, T_{sys}$$

CMB anisotropies for example are 1 part in 10^5

Dicke Switching

Both gain fluctuations and fluctuations in the atmospheric background lead to system noise which is variable. One way to minimize these effects is to make differential measurements of the signal in two feeds (one on source and one not). This method is called Dicke switching after its inventor.



"ESSENTIAL RADIO ASTRONOMY", Condon and Ransom

In this case the system noise compared to source signal is doubled and we have:

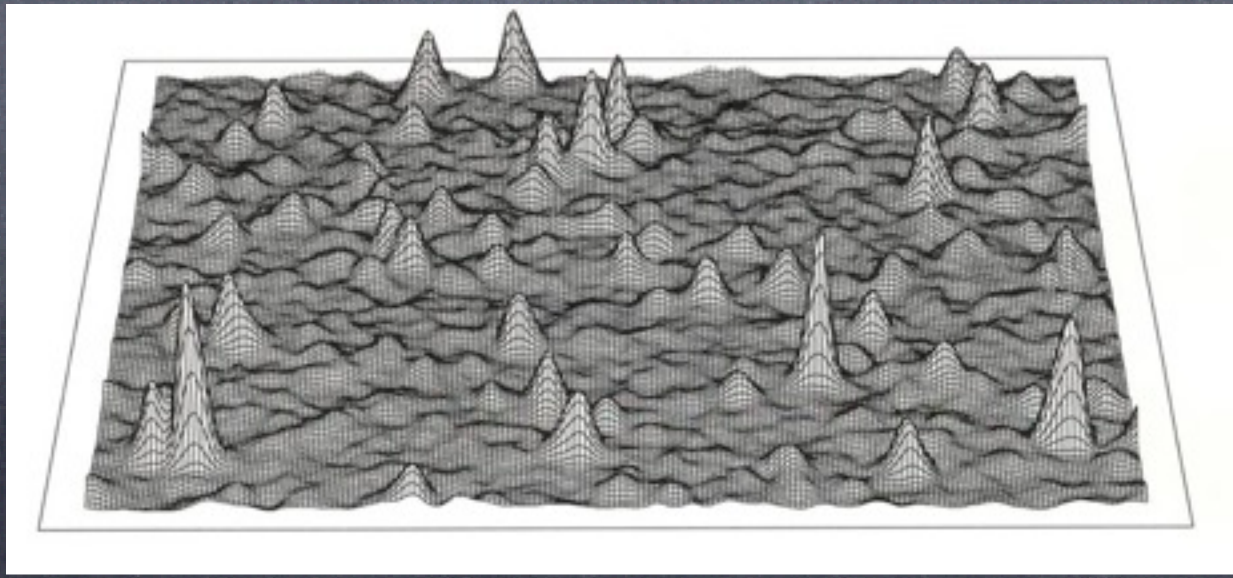
$$\sigma = 2T_{sys}/\sqrt{(\Delta\nu * t)}$$

Similar to chopping in the mid-IR

Confusion

For single dish telescopes which have large collecting areas but bad spatial resolution, confusion is an issue.

Several faint sources within the beam lead to significant sky fluctuations essentially adding background, and this limits the sensitivity particularly at low frequencies.



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Calibration - System Noise

For an atmospheric opacity τ the sum of the noise contribution from the receiver and the atmosphere is:

$$T_{bkgd} = T_{rcvr} + T_{atm} (1-e^{-\tau})$$

The atmosphere also absorbs radiation:

$$T_{detect} = T_{atm} e^{-\tau}$$

To calibrate one first measures an ambient temperature load. Then one measures the sky at a similar elevation to the source. Combining these one can calibrate the receiver noise and measure τ to get the atmospheric absorption and emission.

The system temperature depends on elevation and needs to be remeasured for different sources.

Radio Surveys

(some of many)

VLA FIRST: VLA 20cm survey of 9,900 square degrees of the North Galactic Cap.

NRAO VLA Sky Survey (NVSS): VLA 1.4 GHz survey of sky north of -40 degrees. Images in NED.

HI Parkes All-Sky Survey (HIPASS): HI survey of the sky south of +25 degrees using the 64-m Parkes radio telescope.

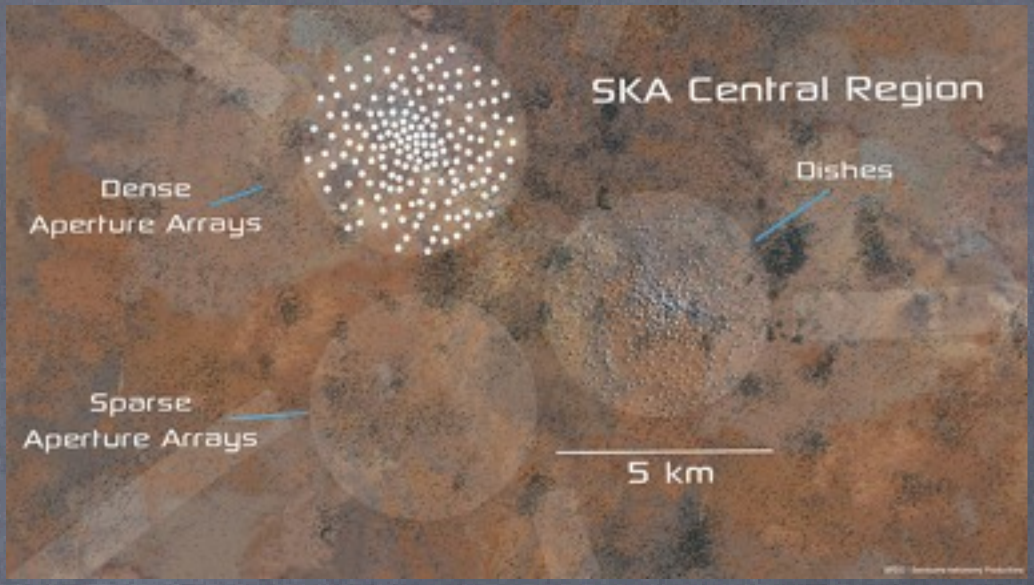
VLA Low-Frequency Sky Survey (VLSS): 74MHz survey covering the sky north of -30°.

Leiden/Argentine/Bonn (LAB) Survey of Galactic HI: All-sky survey of HI in the Galaxy

Westerbork Northern Sky Survey (WENSS): 330 MHz survey of the sky north of 30°.

Future Telescopes

Square Kilometer Array (SKA): circa 2024, collecting area equal to 1 km^2 to be located in the southern hemisphere, longest baseline >=3000 km



Precursors and SKA pathfinders:

- Australian SKA Pathfinder: 0.7-1.8 GHz, 36 12-m dishes, in commissioning
- MeerKAT: 0.5-14 GHz, 64 13.5-m dishes, complete 2016-18, South African project

JVLA: upgrade of the VLA with new electronics and receivers greatly enhancing the performance

Future Telescopes

New Low Frequency Facilities:

LOFAR: 10 - 240 MHz, ~20,000 small antennas over 100 km, partially operational now

LWA: 10-88 MHz, 13,000 antennas over 400 km, 1/53 stations working

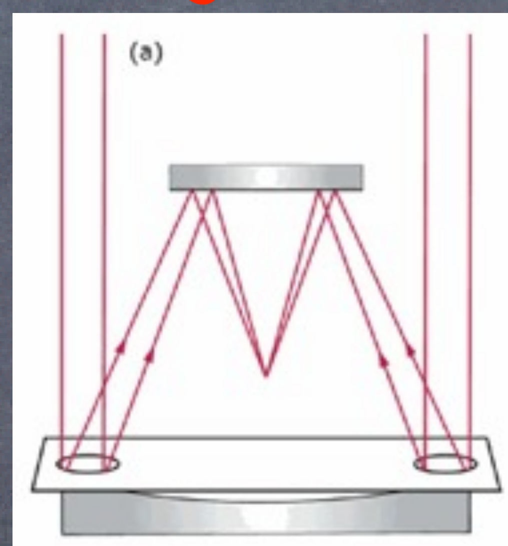
Science with Large Arrays (SKA)

- Probing reionization, primordial gas distribution using 21cm as a function of redshift
- Strong field tests of general relativity using pulsars
- Mapping HI in a billion galaxies to high-z
- Probing cosmic magnetic fields

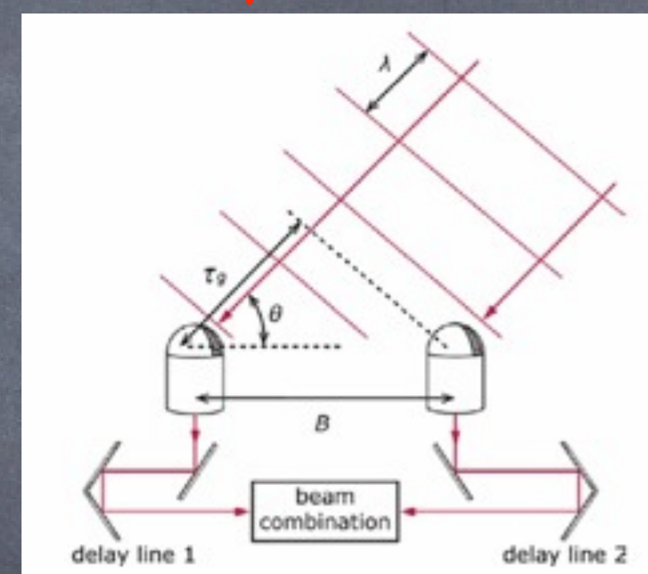
Optical Interferometers

In optical interferometers, light from multiple telescopes is directly interfered rather than being converted to an electronic signal. This places strong limitations on the design and telescope spacing. Two basic designs:

Image Plane



Pupil Plane



delay lines maintain equal path-length

LBT

Keck

Optical Interferometers

For pupil plane (Keck), the phase difference depends on source position on the sky, which limits the field of view.

For image plane (LBT), the field can be larger, but is still limited by phase errors induced by the atmosphere and the size of the area over which this can be corrected (with say AO).

Phase differences between telescopes must be sensed on short timescales to correct for the changing atmosphere, so bright guide star is necessary.

➜ These considerations place strong limitations on optical interferometry.

Atacama Large Millimeter Array (ALMA)

- 66 12-m and 7-m radio telescopes with varying baseline from 150 m to 16 km
- On a plateau in the Atacama desert at 5000 meters
- 0.3-9.6 mm, FOV ~21" at 300 GHz, resolution as good as 6 mas depending on wavelength and configuration
- Cost around $1.3 billion
- Science: first stars and galaxies, star and planet formation, composition of molecular clouds

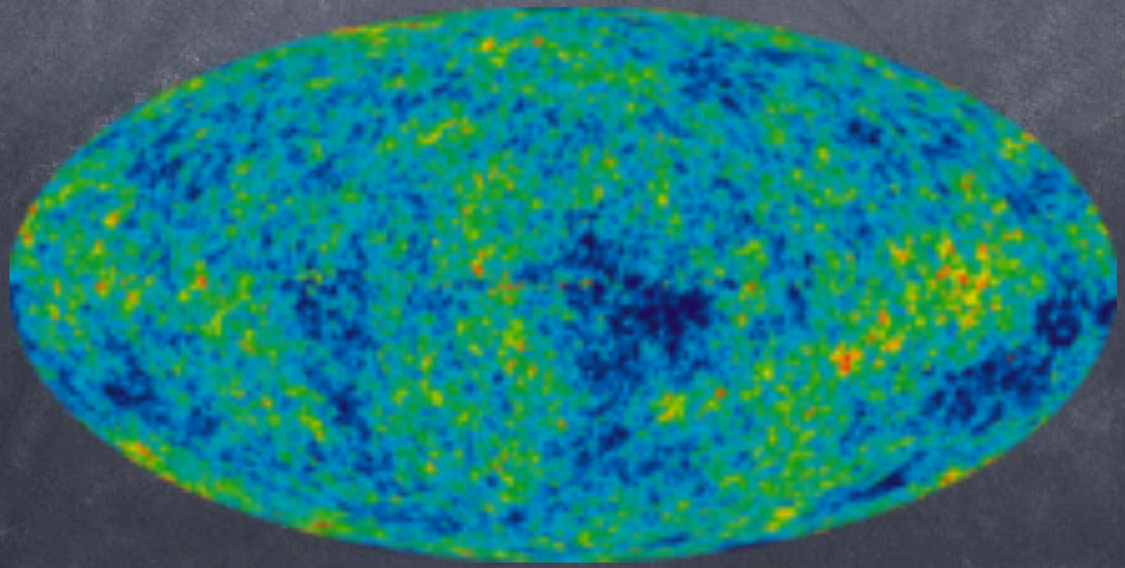
ALMA (ESO/NAOJ/NRAO), Visible: HST

Microwave Astronomy

Science topics:

- CMB anisotropies
- Sunyaev-Zeldovich effect

Despite its unique importance in astronomy, in terms of instruments and the effects of the atmosphere, microwave observing is similar at the short wavelength end to far-IR and at the long-wavelength end to radio.



Microwave Telescopes

Ground-based, single dish:

- South Pole Telescope (SPT): 10-m at South Pole Station, bolometer array, survey of 2500 deg^2
- Atacama Cosmology Telescope (ACT): 6-m telescope in Chile
- Atacama Pathfinder Experiment (APEX): 12-m ALMA prototype

Ground based, arrays:

- Combined Array for Research in Millimeter-wave Astronomy (CARMA): three types of telescopes ranging from 3.5 to 10.4-m combined from previous arrays, molecular gas (CO), SZ clusters
- Arcminute Microkelvin Imager (AMI): 2 arrays of 10-m and 3.6-m telescopes, high-resolution SZ

Satellites:

- WMAP
- Planck

Planck

- Launched May 2009
- 1.9x1.5-m mirror, resolution between 5-33′
- Two instruments one for low frequency (radio receivers) and one for high frequency (bolometers) with a total of nine frequency channels from 30 to 857 GHz
- In addition to the CMB and cluster detection, Planck is producing beautiful maps of the radio emission in the Milky Way.