Essentials of
Radio and (Sub-)Millimeter Astronomy

Fabian Walter (MPIA)

Lecture 5

Radiometers / Receivers II

slides: Essential Radio Astronomy by NRAO (Condon & Ransom)
+ lectures by Ohio State University Professor Adam Leroy
+ ASTRON's Dr. Joeri van Leeuwen

https://www.astron.nl/astrowiki/lib/exe/fetch.php?media=ra_uva:2017:ra_uva_lecture5.pdf

Receiver Systems

Two most common types of receivers in radio astronomy:

Heterodyne receivers
sensitive to the incoming electric field; frequency of the received signal is converted down to a lower frequency by a precise reference signal (mixer) generated locally in the receiver system. Heterodyne receivers are used at metre, centimetre, millimetre and submillimetre wavelengths.

Example in daily life : Cell phone, WiFi antennas. FM and AM radio
Example in the laboratory : spectrum analyzer

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Bolometric receiver
sensitive to thermal-electrical effects; incoming photons are directly detected, heat is generated and the total power (resistance) changes due to material temperature changes.
Bolometers only record the intensity of light but over a very broad range of wavelengths (large bandwidth) e.g. over an entire atmospheric "window" - e.g., 310 GHz to 370 GHz.

Used exclusively at high (sub-mm) wavelengths to do photometry. Usually cooled to milli-Kelvin level to ensure they are limited only by sky background.
Currently no (or very limited via filters) spectral resolution capability.

Receiver Systems: general properties

Good detectors preserve the information contained in the incident e-m disturbance or photon stream. Relevant parameters include:

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(vii) Spectral resolution - smallest frequency interval over which the detector is sensitive to incoming radiation.

Radiometers

A **radiometer** is a device to measure the noise coming out of a radio telescope.

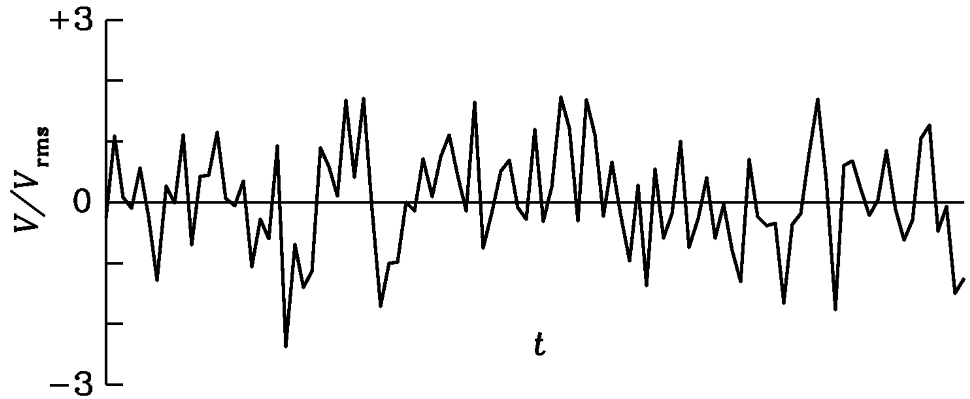
The radiometer equation is among the most often-used tools of radio astronomy. For observations with a bandwidth Δv averaged over a time t, it predicts the uncertainty in the noise power from a telescope to be:

$$\sigma_{\rm T} \approx \frac{T_{\rm s}}{\sqrt{\Delta\nu_{\rm RF}\tau}}$$

That is: the uncertainty in your measurement of power out from your telescope averages as the square root of time and bandwidth included in the measurement with the scale set by a system temperature that reflects the total noise power incident on the telescope.

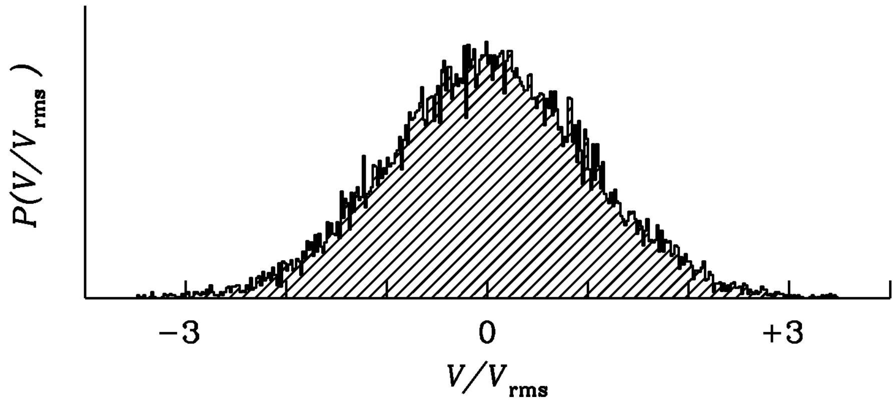
Radiometers: Noise

Simulation of the voltage out of a radio telescope as a function of time:



The mean of the voltage is zero and there is a characteristic scale to the amplitudes.

Let's instead plot the distribution of amplitudes used to make this plot.



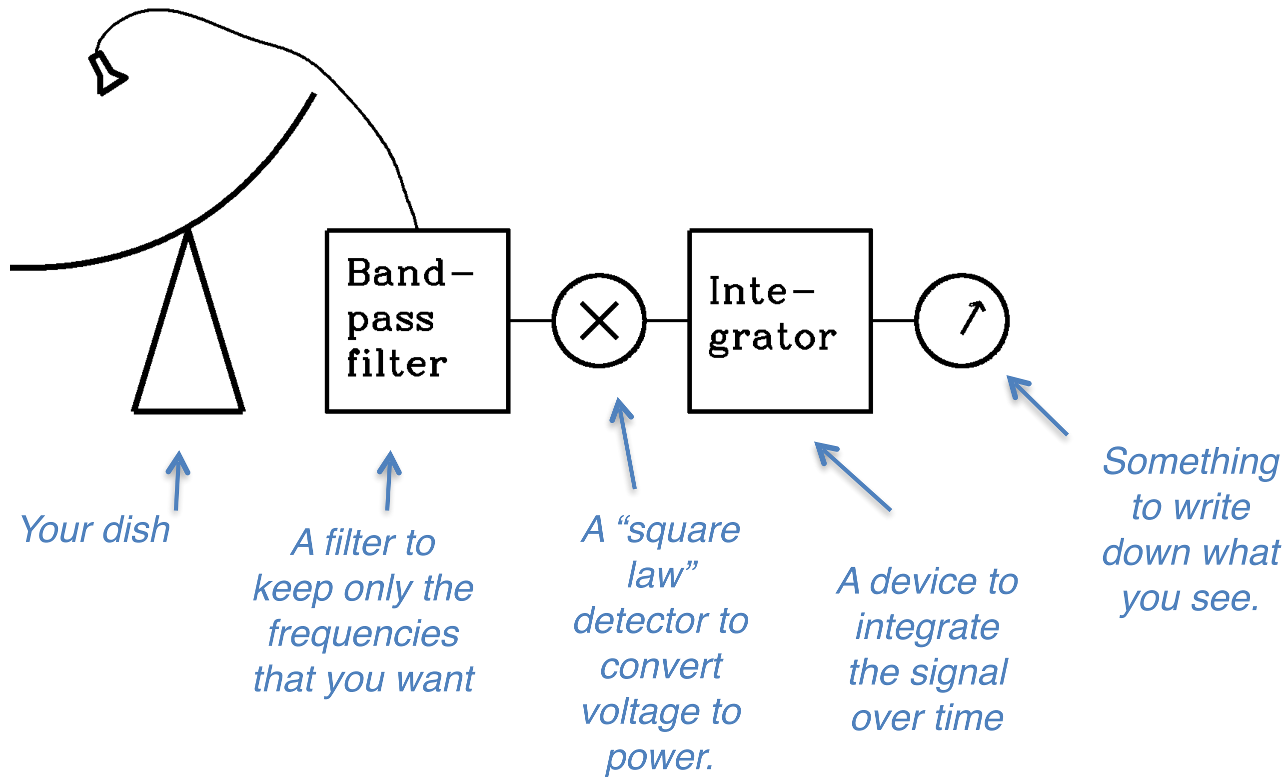
Histogram of voltages. Note that there is a characteristic scale along X and there is a Gaussian distribution.

This is a reasonable example of what you might be getting out of the back of a telescope.

The most basic radiometer

Say we want to measure the power at ν_{RF} with some finite bandwidth $\Delta\nu_{RF}$ – the most basic instrument for doing this needs to:

(1) Select only the frequencies that we care about.
(2) Translate voltage into a power that we can measure.
(3) Integrate the stream of time measurements into a single value



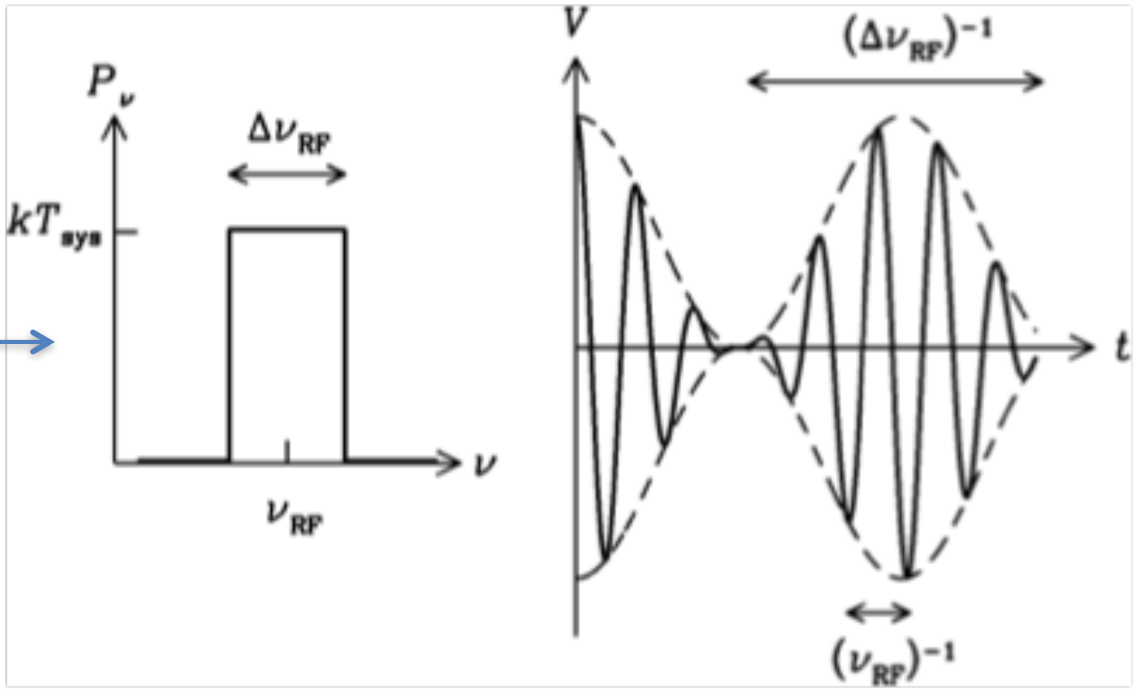
bandpass filter

The first step in this chain is usually a bandpass filter that allows only a range of frequencies that is typically pretty narrow compared to the central frequency to pass through:

$$\nu_{\rm RF} - \frac{\Delta\nu_{\rm RF}}{2} \ \ \text{to} \ \ \nu_{\rm RF} + \frac{\Delta\nu_{\rm RF}}{2}$$

The idea is to measure the power only over this finite part of the band. The effect of such a filter is also to imprint some overall structure on the time series of the voltage. Which now looks like the pattern below:

We want to get just this:



Passing random signals through a filter like this produces this: a main frequency behavior at the central frequency and an envelope set by the filter width.

radiometers: square law detector

Measuring the raw voltage from the telescope would give you a rapidly wiggling voltage about a mean of zero. To get the average power we need to build a detector, something that lets us get at the amplitude distribution of input voltage. The simplest such device just squares the input voltage. Square of the voltage gives us power and this makes the output positive, averageable, with a mean reflective of the average amplitude (which is our goal).

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Imagine we have an input voltage where we have filtered to get about v_{RF}:

$$V_{\rm i} \approx \cos(2\pi\nu_{\rm RF}t)$$

Then the square law detector outputs this as:

$$V_{\rm o} \propto \cos^2(2\pi\nu_{\rm RF}t)$$

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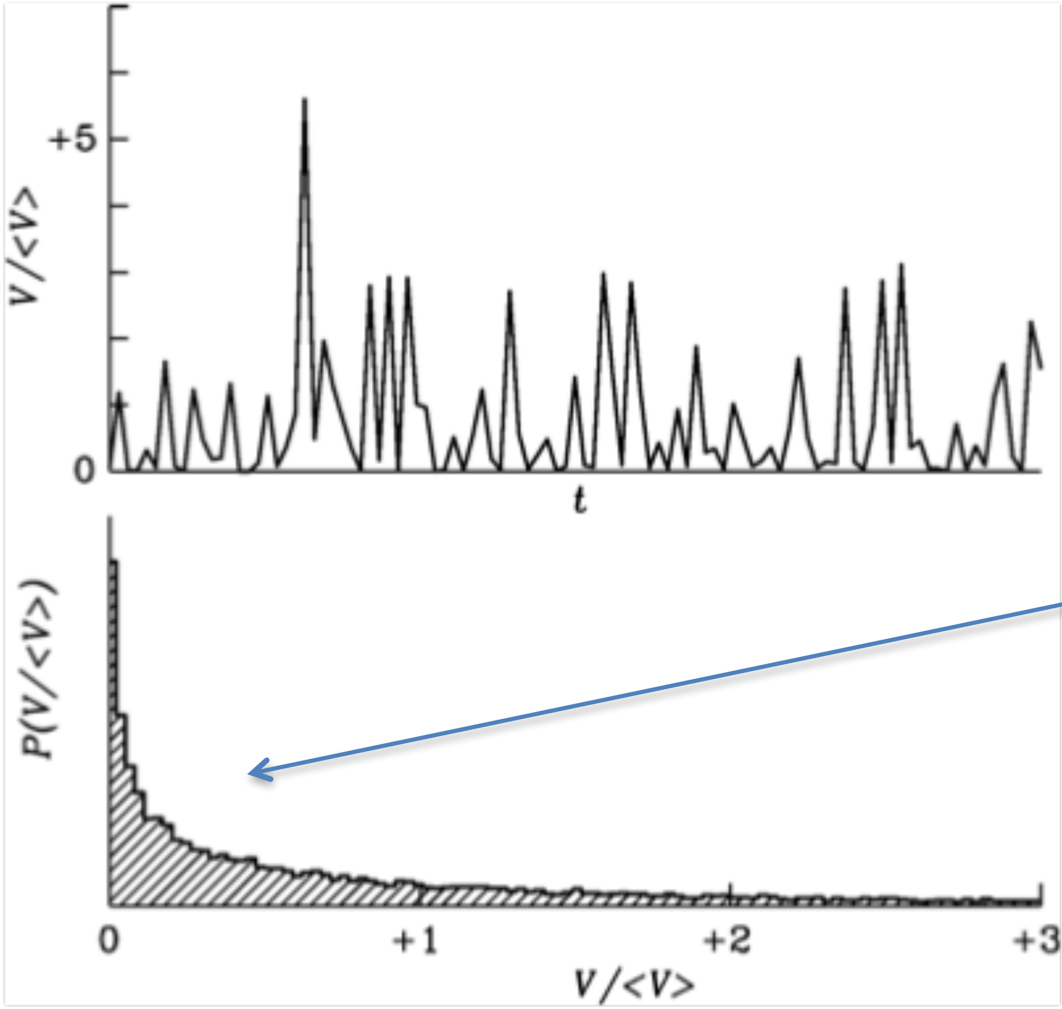
NOTE: The noise is increased by multiplying the signal by itself. For a square-law detector the noise increases by a factor of **sqrt(2)**.

radiometers: square law detector

So after passing through the square law detector we get only positive values

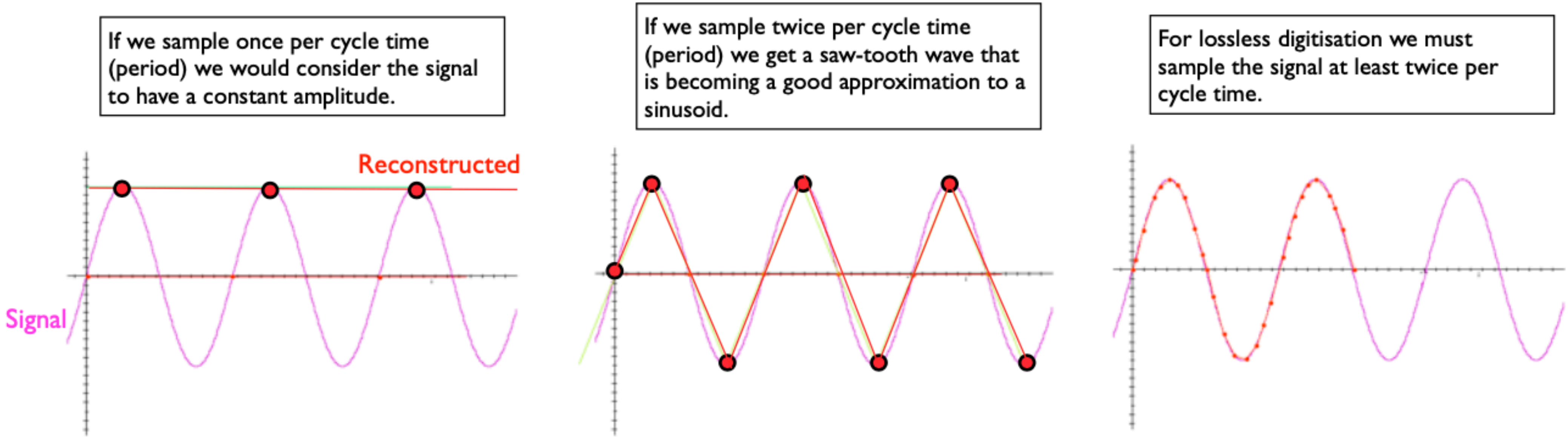
Voltage vs. time coming out of a square law detector.



Probability distribution (i.e., histogram) of the voltages coming out of the square law detector. They are positive and link back to the mean average amplitude.

Sampling

How often must we sample the signal ? Consider the following sine wave:

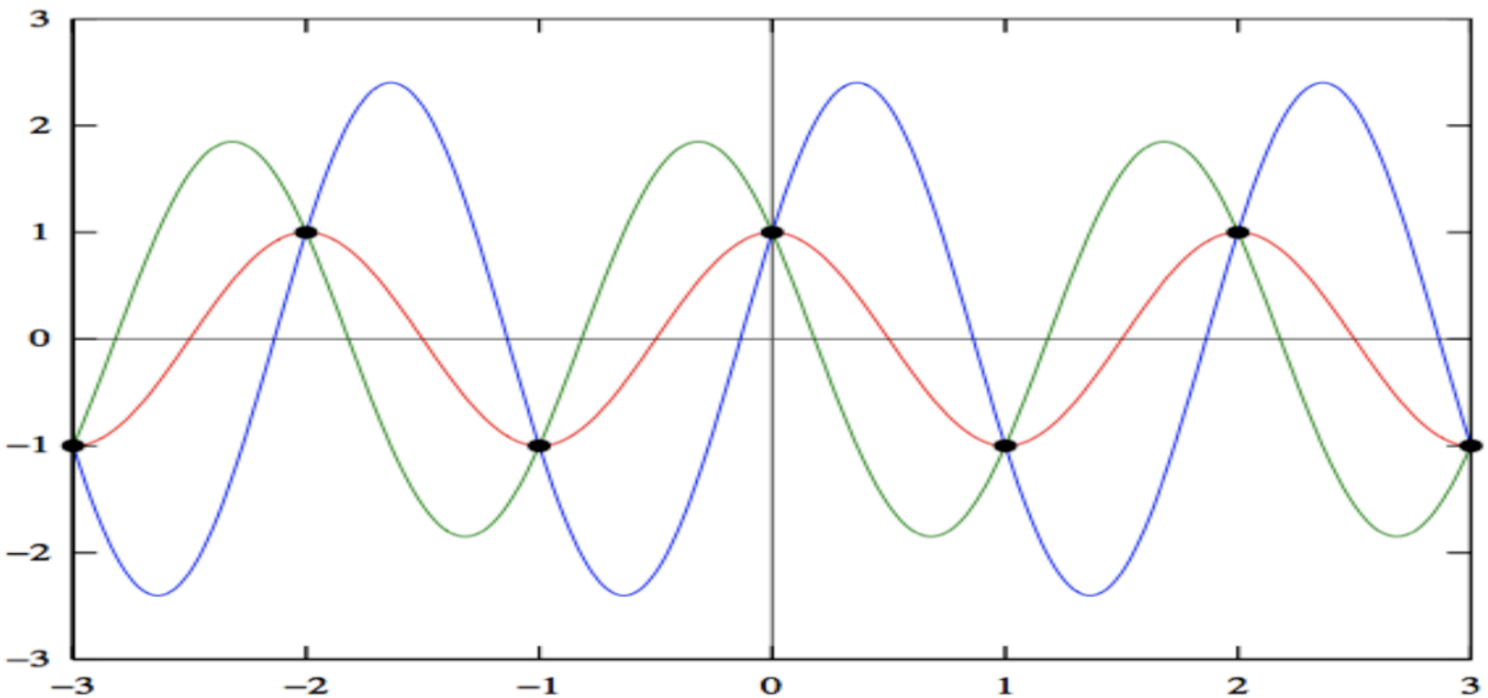


Nyquist's sampling theorem states that for a limited bandwidth signal with maximum frequency f_{max}, the equally spaced sampling frequency f_s must be greater than twice the maximum frequency f_{max}, i.e. $f_s > 2 \cdot f_{max}$ in order for the signal to be uniquely reconstructed without aliasing.

The frequency $2f_{max}$ is called the Nyquist sampling rate.

Sampling

Note that strictly speaking, the sampling frequency (rate) must be strictly greater than the Nyquist rate ($f_s > 2 \cdot f_{max}$) of the signal to achieve unambiguous representation of the signal. In the pathlogical case where the signal contains a frequency component at precisely the Nyquist frequency, then the corresponding component of the sample values cannot have sufficient information to reconstruct the signal.



A family of sinusoids at the critical frequency, all having the same sample sequences of alternating +1 and −1. That is, they all are aliases of each other, even though their frequency is not above half the sample rate. Note that strictly speaking, the sampling frequency (rate) must be strictly greater than the Nyquist.

radiometers: sampling and integration

Putting this together:

1. The noise out from the square law detector is sqrt(2) times the noise power coming out of the telescope.

2. Integrating over Δv and τ, we get Δv τ samples. Combining these we can constrain the average output power better by a factor of 1/sqrt(N) = 1/sqrt(Δv τ).

So this means that the uncertainty in our ability to measure the noise power of the telescope for an observation of length τ and bandwidth Δv is just:

$$\sigma = \frac{P_{noise}}{\sqrt{\Delta \nu \tau}} \qquad \sigma_{\mathrm{T}} \approx \frac{T_{\mathrm{s}}}{\sqrt{\Delta \nu_{\mathrm{RF}} \tau}} \qquad P=kT$$

Noise

Thermal noise (Johnson noise) exists in all electronic components and results from the thermal agitation of free-electrons. The noise is typically "white noise" (flat power response with frequency).

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In electronics, the noise temperature is a temperature (in Kelvin) assigned to a component such that the noise power delivered by the noisy component is given by,

$$P \sim kT$$

The noise contributions of the various components in a receiver system are usually independent (uncorrelated) and the total noise in a receiver system (T_{RX}) can be estimated by summing all the individual contributions.

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The total system temperature, T_{SYS} , is noise from the whole system and includes the antenna Temperature (noise from the sky background, atmosphere, losses in the feed, spillover from the ground) plus the noise from the receiver system itself:

$$T_{SYS} = T_A + T_{RX} = T_{sky} + T_{atm} + T_{loss} + T_{spill} + T_{RX} + \ldots$$

At centimetre and millimetre wavelenghts, T_{RX} dominates the system noise temperature.

Noise - detection of CMB

When Penzias & Wilson made their measurements, they found:

T_{atm} = 2.3 +/- 0.3 K,
T_{loss} = 0.9 +/- 0.4 K,
T_{spill} < 0.1 K.
And they expected T_{sky} ~ 0.

So looking straight up, they expected to measure $T_{A,}$

T_A = 2.3 + 0.9 + 0.1 + 0 = 3.2 K.

….but what they found was T_A = 6.7 Kelvin!

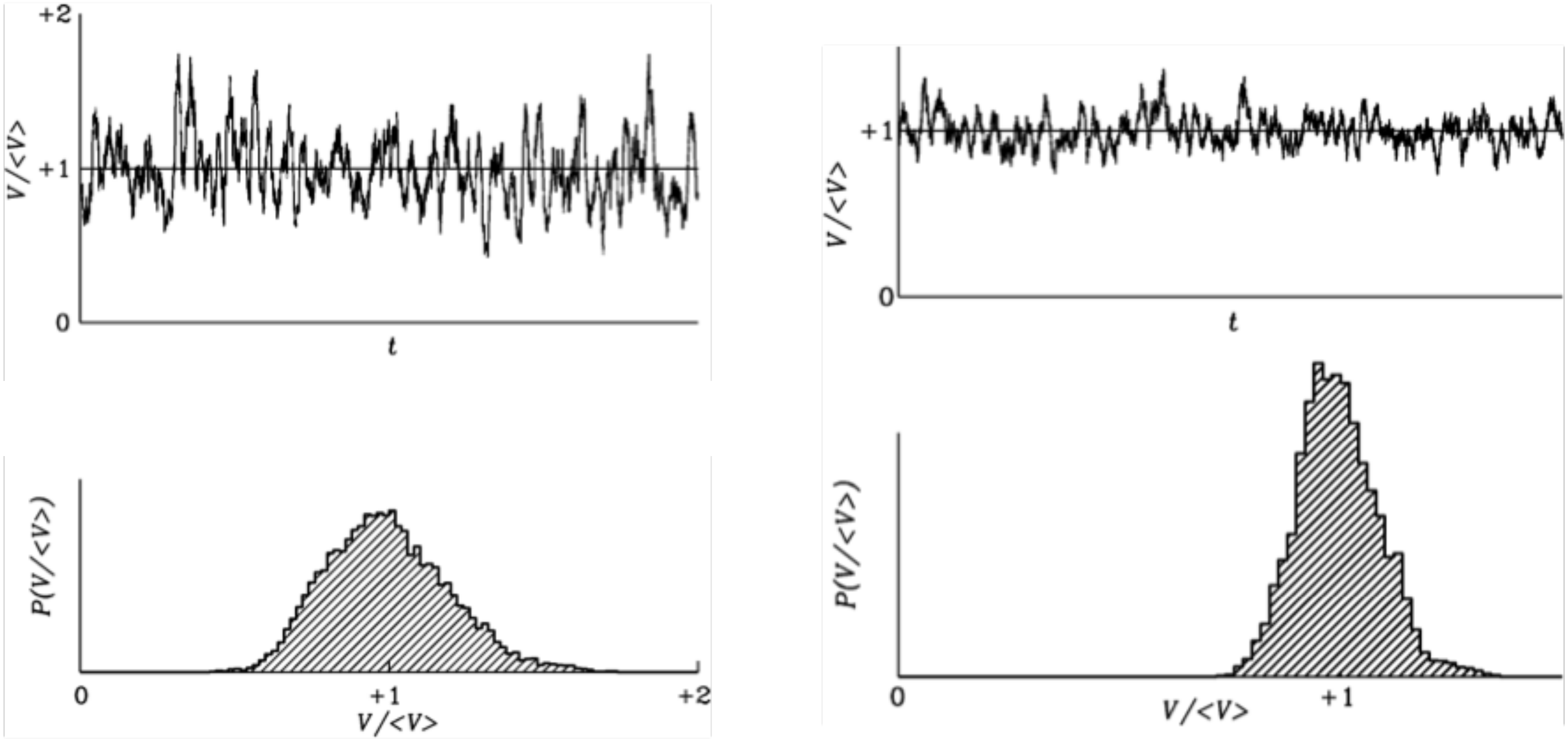
The excess was the CMB and Galactic emission.

radiometers: sampling and integration

A practical example

$$\sigma_{\mathrm{T}} \approx \frac{T_{\mathrm{s}}}{\sqrt{\Delta\nu_{\mathrm{RF}}\tau}}$$

Two cases observing the same power source but on the left the smoothing (and so Δν τ) is four times that on the left. Note the same mean but the lower RMS scatter on the right.



radiometers: implications

$$\sigma_{\rm T} \approx \frac{T_{\rm s}}{\sqrt{\Delta\nu_{\rm RF}\tau}}$$

There are a few things to realize here:

(1) $\Delta\nu$ and τ are big numbers. The uncertainty in the total noise power ends up being a tiny fraction of the overall noise power. This is important because astronomical sources are very faint (noise power far sub-K) compared to any realistic T_S.

(2) You want a cold telescope. A cool receiver, low spillover, etc. mean that T_s is low and allow you to achieve the same sensitivity much faster. Put another way linear (T_S) is much faster than sqrt (integration time)!

(3) Your single dish radio measurements are basically measuring a tiny astronomical bump on top of a big (10s, 100s, even 1000s) of K total power.

radiometers: in practice

Recall that when pointed at our source:

$$T_{sys}^{ON} = T_{CMB} + T_{receiver} + T_{atm} + \ldots + T_{source}$$

What we want

Now imagine looking at an otherwise identical patch of sky just off to to the right, here:

$$T_{sys}^{OFF} = T_{CMB} + T_{receiver} + T_{atm} + \ldots$$

The second measurement captures all of the “other stuff” so that:

$$T_{source} = T_{sys}^{ON} - T_{sys}^{OFF}$$

How well do we know T_{source}? From error propagation: $\sigma_{source} = \sqrt{\sigma_{T,on}^2 + \sigma_{T,off}^2}$

radiometers: in practice

Imagine that we make identical observations of the two positions each for τ/2:

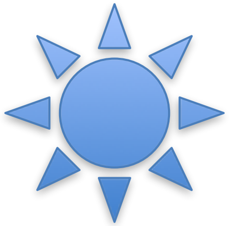
$$\sigma_{source} = \sqrt{\sigma^2_{T,on} + \sigma^2_{T,off}} = \sqrt{2}\sigma_T = \sqrt{2}\frac{T_S}{\sqrt{\Delta\upsilon\tau / 2}} = 2\frac{T_S}{\sqrt{\Delta\upsilon\tau}}$$

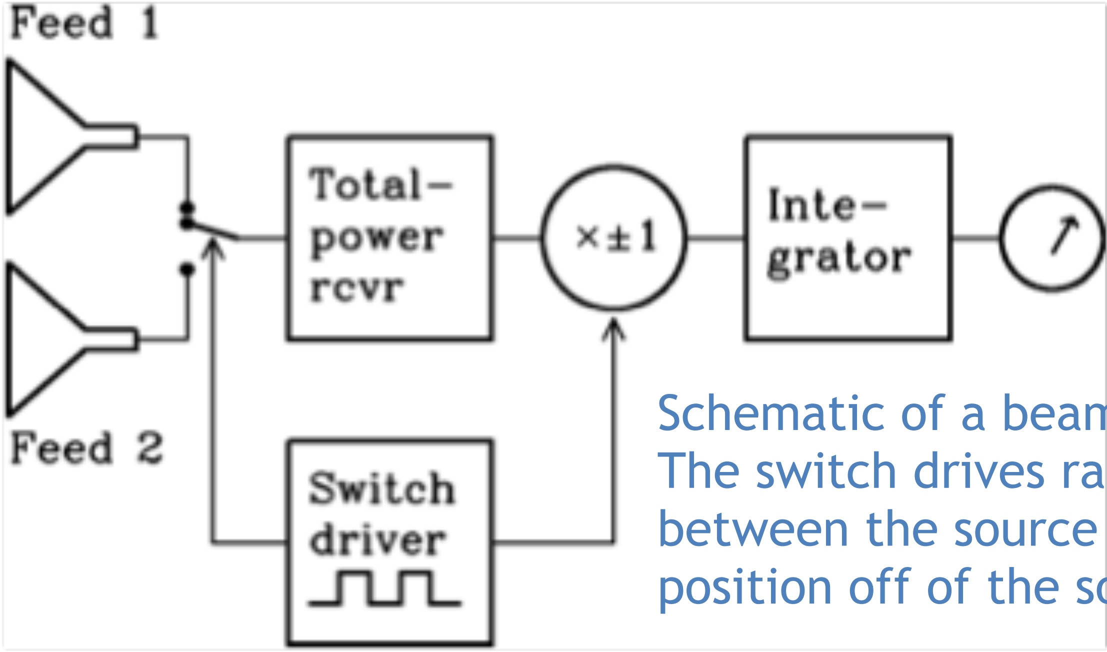
With one sqrt(2) reflecting the extra noise from subtracting (or adding) two pieces of noise and the other sqrt(2) reflecting that you spend half the time "ON" and half "OFF."

Most of the time practically you will do something like this differential measurement. Depending on your strategy you may get this factor of two or you may do a little bit better (e.g., if you use one OFF for many observations or do some other clever trick).

radiometers: Dicke Switching

A hardware oriented approach of this differential measurement:





Schematic of a beam switching system. The switch drives rapid variations between the source and a reference position off of the source.

And the cost of this approach is sensitivity, which is only half of that in an absolute setup. To see the factor of two consider that only half the total time τ is spent on source while the noise is sqrt(2) higher due to the difference operation (which adds noise quadratically):

pros: no actual movement of the telescope
cons: Feed 2 may have different properties from Feed 1

Beyond the Radiometer Equation

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(3) Non-Gaussian fluctuations in the atmosphere introduce systematic effects.

Integrate long enough with a single dish telescope and you are likely to run up against one of these effects.

Gain Variations

Real electronic systems at telescopes have some gain, G, which acts multiplicatively on the signal.

$$P_\nu = GkT_\mathrm{s}$$

Instability in the signal path can cause this gain to experience small fluctuations over time. Then the output power is affected:

$$\Delta P_\nu = \Delta GkT_\mathrm{s}$$

Which looks like a changing system temperature over time:

$$\Delta T_\mathrm{G} = T_\mathrm{s}\left(\frac{\Delta G}{G}\right)$$

And accordingly adds another noise term to what we measure:

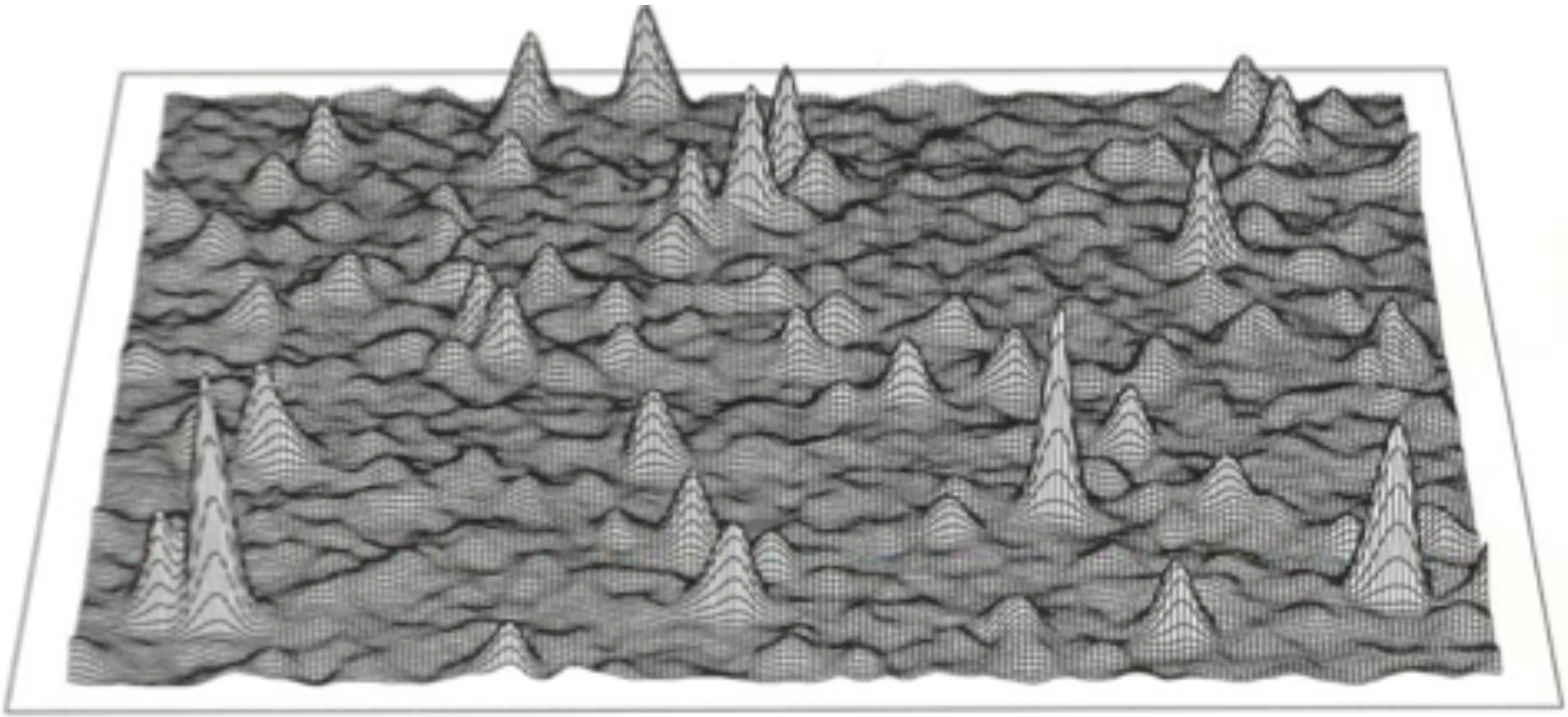
$$\sigma^2_\mathrm{total} = \sigma^2_\mathrm{noise} + \sigma^2_\mathrm{G}$$

$$\sigma^2_\mathrm{total} = T_\mathrm{s}^2\left[\frac{1}{\Delta\nu_\mathrm{RF}\tau} + \left(\frac{\Delta G}{G}\right)^2\right]$$

Confusion

The radio sky is full of sources and the beam patterns for single dish telescopes in particular are often very large. It is entirely possible to get into a regime in which there are astronomical sources inside your beam contributing power at a level comparable to or greater than your radiometer noise. In this case your measurement is not limited by radiometer noise but by **confusion**.

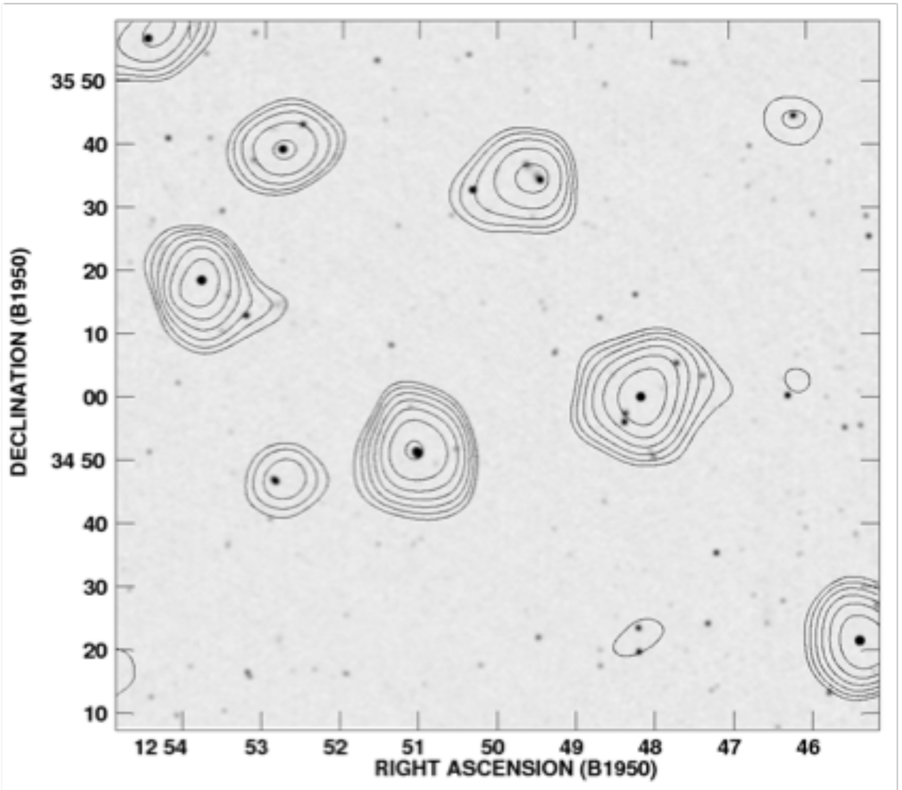
A power image of the northern sky. The ripples are real sources:



Confusion

A practical empirically derived relationship is: $\left(\frac{\sigma_c}{\text{mJy beam}^{-1}}\right) \approx 0.2\left(\frac{\nu}{\text{GHz}}\right)^{-0.7}\left(\frac{\theta}{\text{arcmin}}\right)^2$

Which works at low frequencies and reflects that confusion is dominated by extragalactic point sources with nonthermal spectra and that the degree to which you are confused depends on the size of the beam with which you observe. Different expressions but similar concerns apply in the infrared regime (e.g., *Herschel* was confusion limited at 200-500µm).



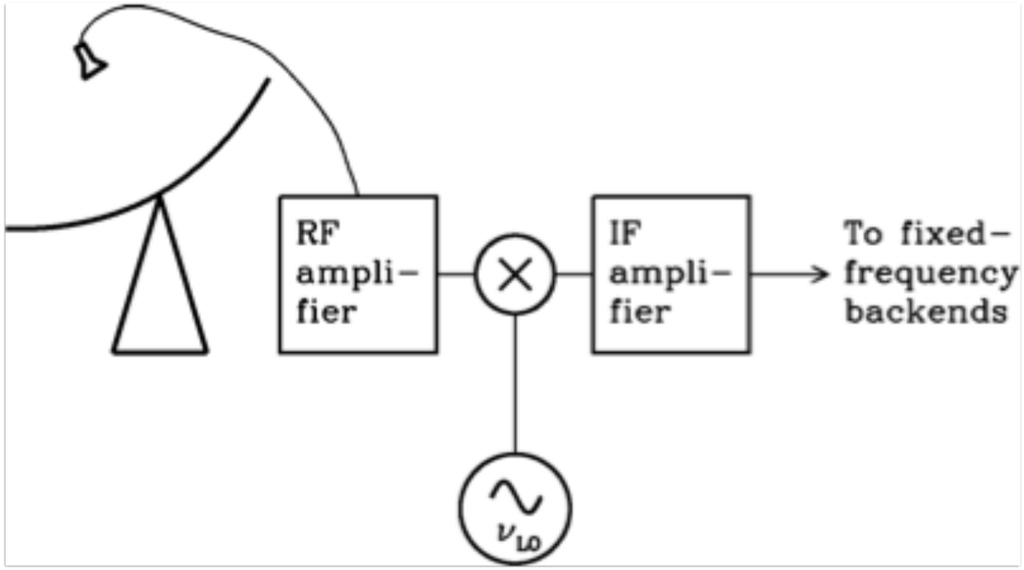
See the practical difference between the sky observed with the VLA (in gray) and with the GBT (in contour). Confusion depends on your angular resolution (note that at low frequencies it is still very easy to be dominated by confusion with the VLA in its compact configurations).

Heterodyne Receivers

The simple block diagram that we used for radiometers is more complicated in a real system.

Radio telescopes almost always use some form of heterodyne mixing to manipulate the incoming signal before running it through most of the electronics of the system.

The block diagram for such a system looks like:



Where the operative "heterodyne" part is the cross and the squiggle: the incoming signal, after amplification, is mixed with a local oscillator of a known frequency. The two waves interfere with one another and produce a signal with frequency equal to the difference of the incoming radio light and the local oscillator.

Heterodyne Receivers

The two waves interfere with one another and produce a signal with frequency equal to the difference of the incoming radio light and the local oscillator.

$$v_{RF}(t) = \cos 2\pi f_{RF} t,$$

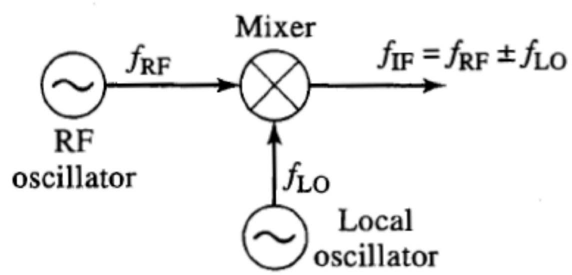
(radio) frequency being observed

$$v_{LO}(t) = \cos 2\pi f_{LO} t.$$

Local Oscillator - This can be set by the observer

That is, once the signals are mixed you get the multiplication of the two:

$$v_{IF}(t) = K\, v_{RF}(t) v_{LO}(t) = K \cos 2\pi f_{RF} t \cos 2\pi f_{LO} t$$
$$= \frac{K}{2}[\cos 2\pi (f_{RF} - f_{LO})t + \cos 2\pi (f_{RF} + f_{LO})t]$$

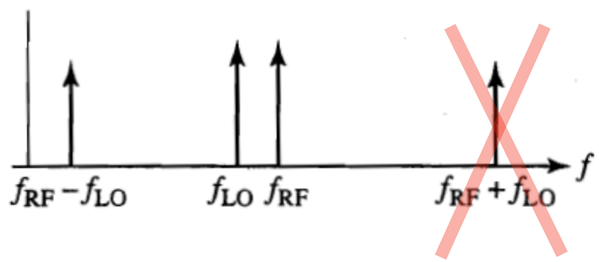


*One term has frequency of the **difference** in original frequencies.*

*One term has frequency of the **sum** in original frequencies.*

$$f_{IF} = f_{RF} - f_{LO}$$

IF: intermediate frequency — can be selected by electronics / filtering



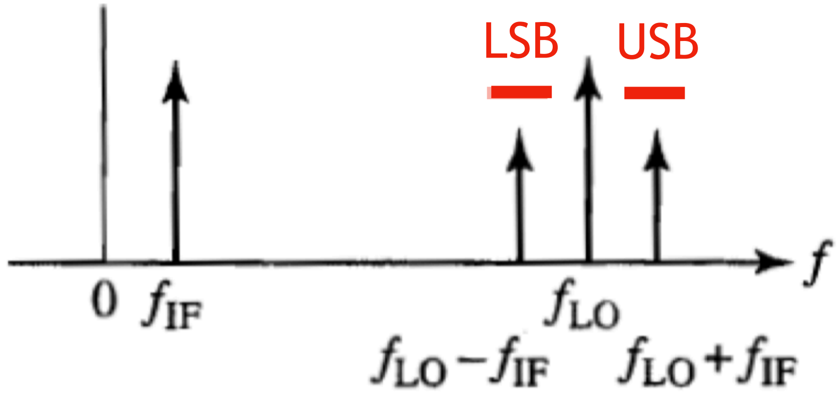
Heterodyne Receivers

Note: 'image frequency' is also mixed down to the same IF!

$$f_{IM} = f_{LO} - f_{IF}.$$

$$f_{RF} = f_{LO} + f_{IF},$$

from: $f_{IF} = f_{RF} - f_{LO}$



In the old days this was a problem - as one could not tell whether lines were observed in the upper or lower sidesband (USB or LSB).

Single sideband receiver (SSB): only one sideband makes it through systrem.
The other (image) sideband received is rejected

Dual sideband receiver (DSB): both sidebands are superposed.

Sideband seperating receiver (2SB): both sidebands are recorded separately - this is achieved, eg. Using 2 LOs, and shifting one LO by 90 degrees. This Became achievable in the early 2000s.

Currently most receivers (ALMA etc) are 2SB receivers.

Heterodyne Receivers

A heterodyne receiver mixes the signal and filters it down to a lower, intermediate frequency set by the electronics. Why is this useful?

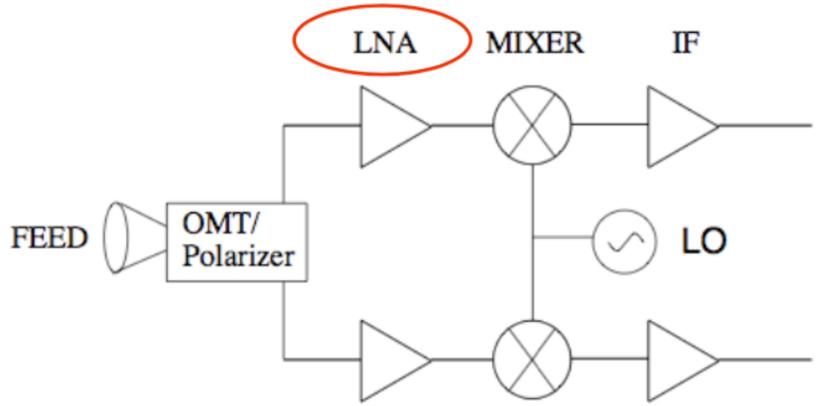
(1) Generically, it's easier to work with lower frequencies.

(2) It means that by tuning a single local oscillator, the input frequency for any of a wide range of radio frequencies can be fed into the electronics at a controlled **intermediate frequency (IF)**.

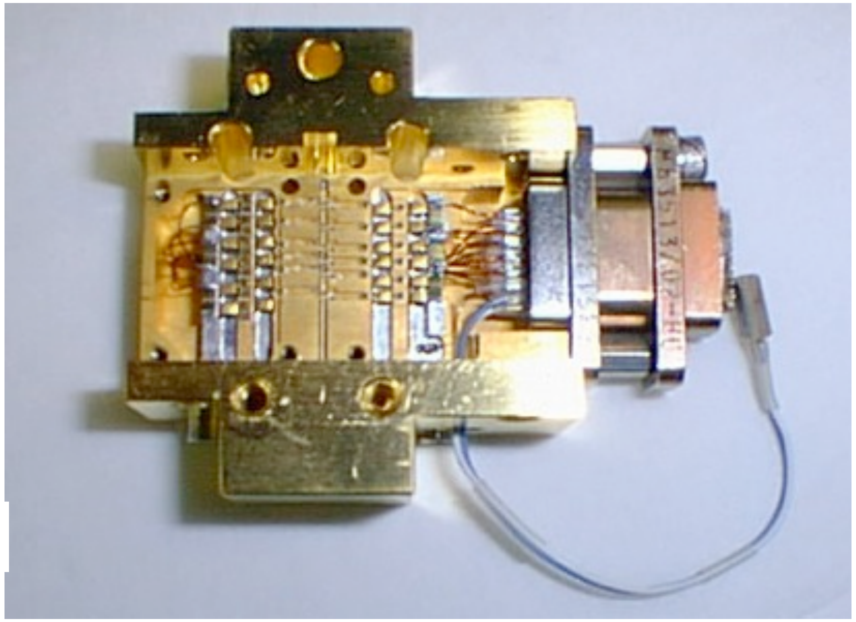
(3) That means you can build **one set of electronics** to process this IF (so-called "backends") that can be used across the spectrum.

Heterodyne Receivers

A typical heterodyne radio astronomy receiver system. The receiver amplifies the incoming signal from the feed, filters the signal and "down-converts" it to a lower frequency where it can be more easily sampled or detected.



Some feeds inherently detect and separate polarisations, other types require orthomode transducers (OMT - see above) to separate channels.



LNA = Low Noise Amplifier - amplifies the incoming signal - LNAs are usually cryogenically cooled to minimise the noise they also add to the overall system.

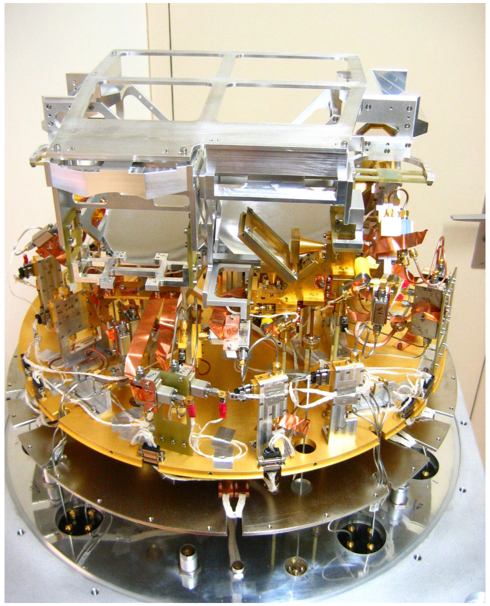
multi-beam receivers

note: usually, single-pixel receivers. it's like having a CCD with one pixel

solution: multi-beam receivers

Parkes 21cm multi beam

(13 beams)



IRAM HERA receiver (9 beams)

multi-beam receivers

7-pixels prototype for a 230 GHz multi-beam receiver

D. Maier, A.L. Fontana, M. Parioleau, Q. Moutote, J. Reverdy, A. Barbier,D. Billon-Pierron, E. Driessen, and J.M. Daneel
Institut de RadioAstronomie Millimétrique, St. Martin d'Hères, France
Contact: maier@iram.fr, phone +33 76 89 49 16

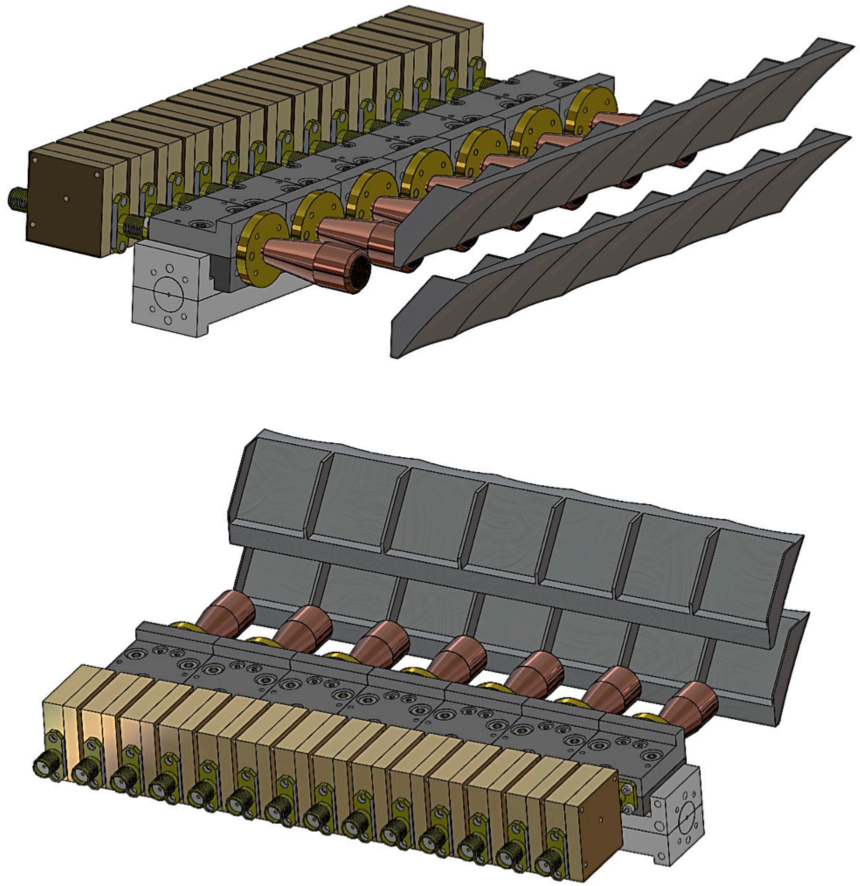
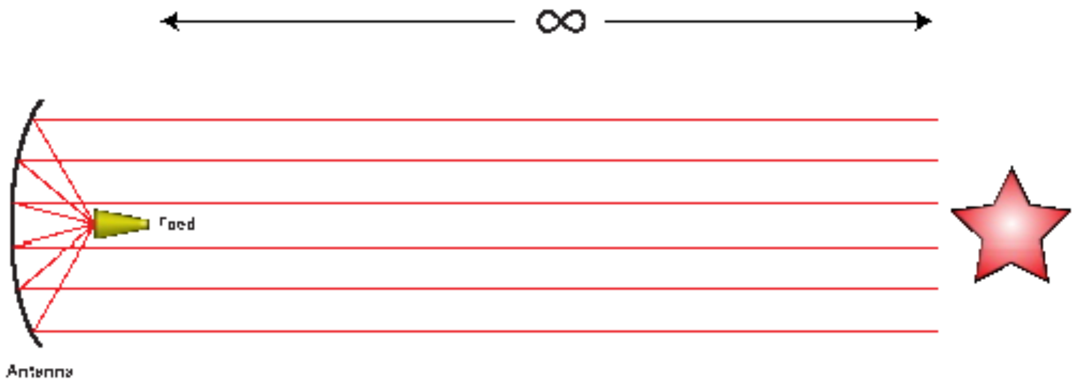
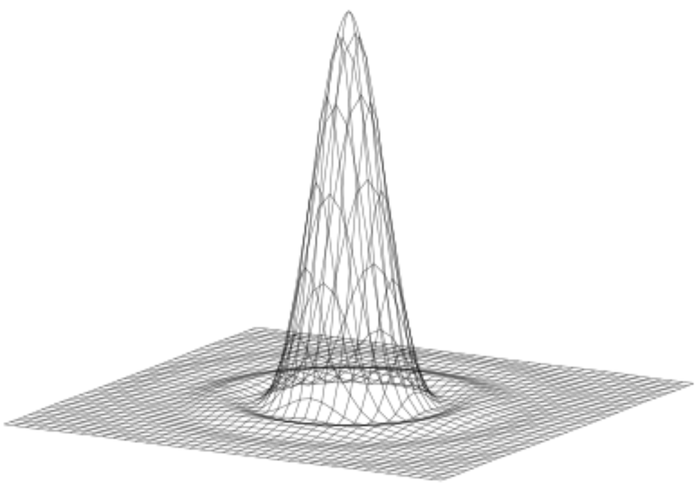


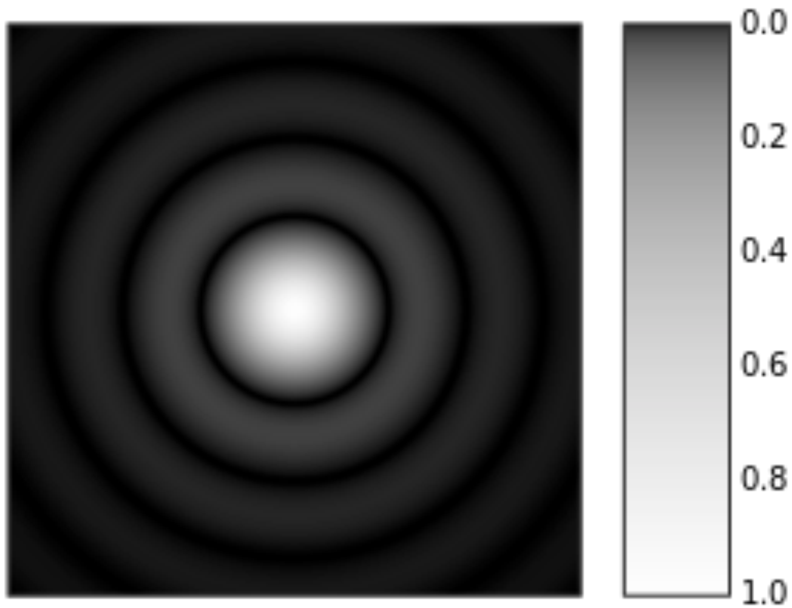
Fig. 8: Views of the 7-pixels array with its individual optics, composed of two multi-mirrors.

Radio Telescopes / Antennas



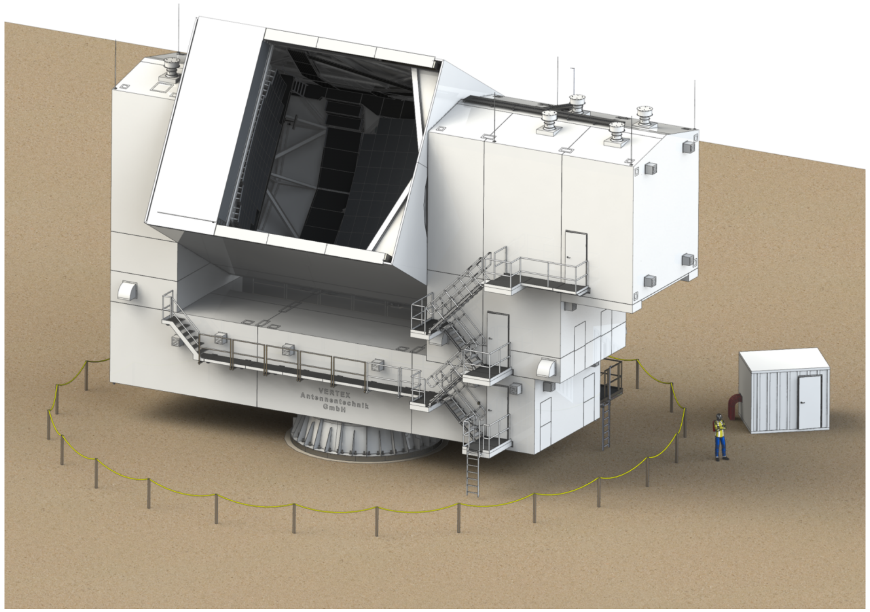
consider additional effects if you are not on-axis



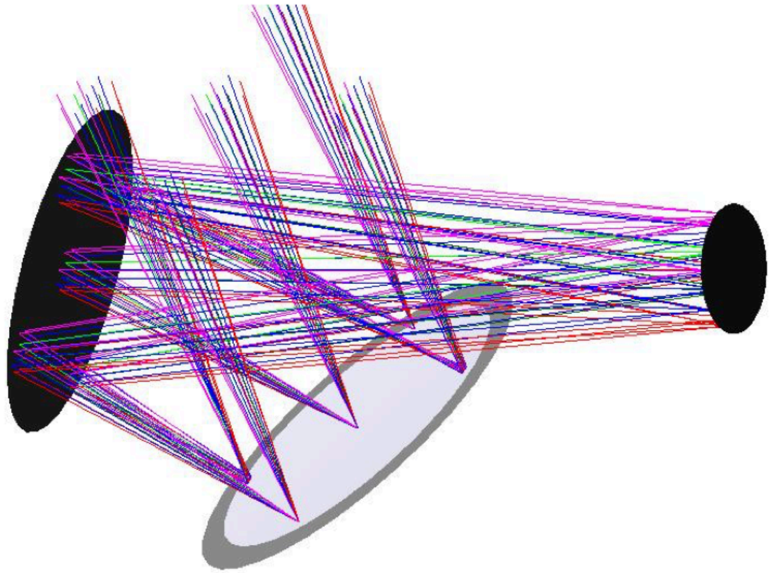


e.g. CCAT-prime - extremely wide FOV

now called: Fred Young Submillimeter Telescope (FYST)



altitude of 5,612 metres (18,412 ft), on Cerro Chajnantor mountain/ summit



Schematic layout of a crossed-Dragone telescope. Light from the sky is reflected first off a primary mirror and then off a slightly smaller secondary before reaching the instrument port on the side. This mirror combination permits a high throughput of the light over a very wide field of view and delivers a flat focal plane that will accommodate hundreds of thousands to millions of detectors. Sketch by Cornell Professor Mike Niemack.

Bolometers

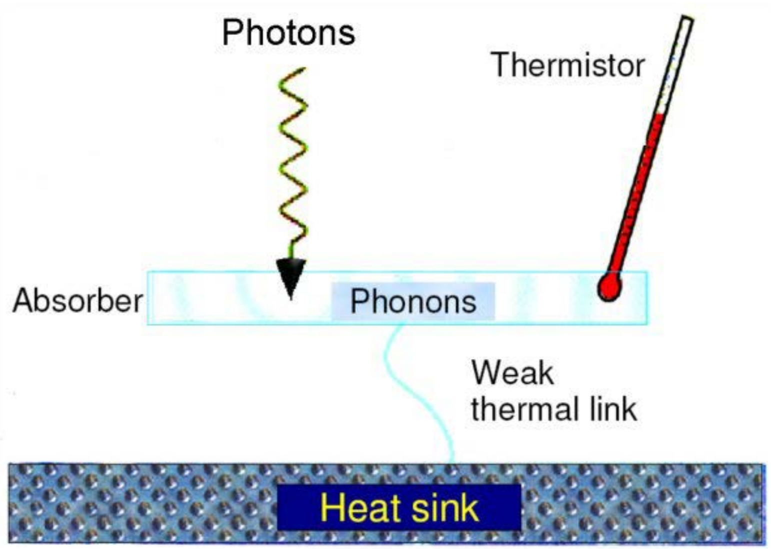
Bolometers as very sensitive thermometers

Composite of an absorber and the actual thermometer (thermistor)

The absorber is kept at very low temperature (0.3 degree above absolute zero) by a weak thermal link to a heat sink.

Electromagnetic radiation (photons) is absorbed.
→ energy is transferred to the absorber whose temperature will increase

→ An ultra-sensitive thermometer (thermistor) transforms the temperature variations of the absorber in electric signals, consequently amplified and digitally processed by computers.



Bolometers

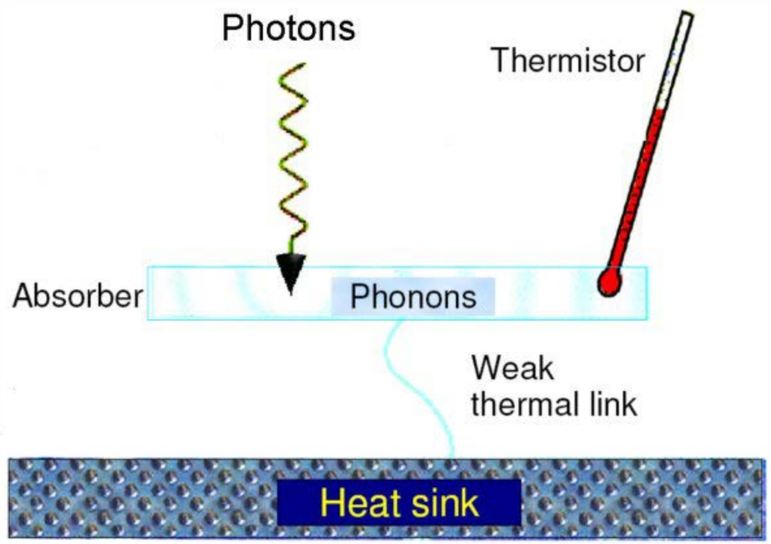
Most useful application in the (sub-)mm range: 60 µm – 3.4 mm wavelength

→ at shorter wavelength: photo-electric effect in Ge:Ga or Silicon can be exploited better —> CCD

→ at longer wavelength: photons deposit less and less energy into the absorber material —> heterodyne receivers

Bolometers are not strongly discriminating regarding the spectral range of the incoming radiation

→ spectral range (pre-)selection by means of feed horns and filters necessary
→ wide spectral bandwidth input easily possible



Bolometers

Advantage of the composite concept:

- individual bolometers can be packed together → bolometer arrays filling more of the focal plane than just one beam width

Issues:

strong cooling of the bolometers is mandatory to suppress thermal noise. Usually, liquid helium is used as coolant.
But: temperatures far below 1 Kelvin are necessary ↔ 4He gets superfluid at ~2 K

…use 3He instead ... does not become superfluid, but is much more rare

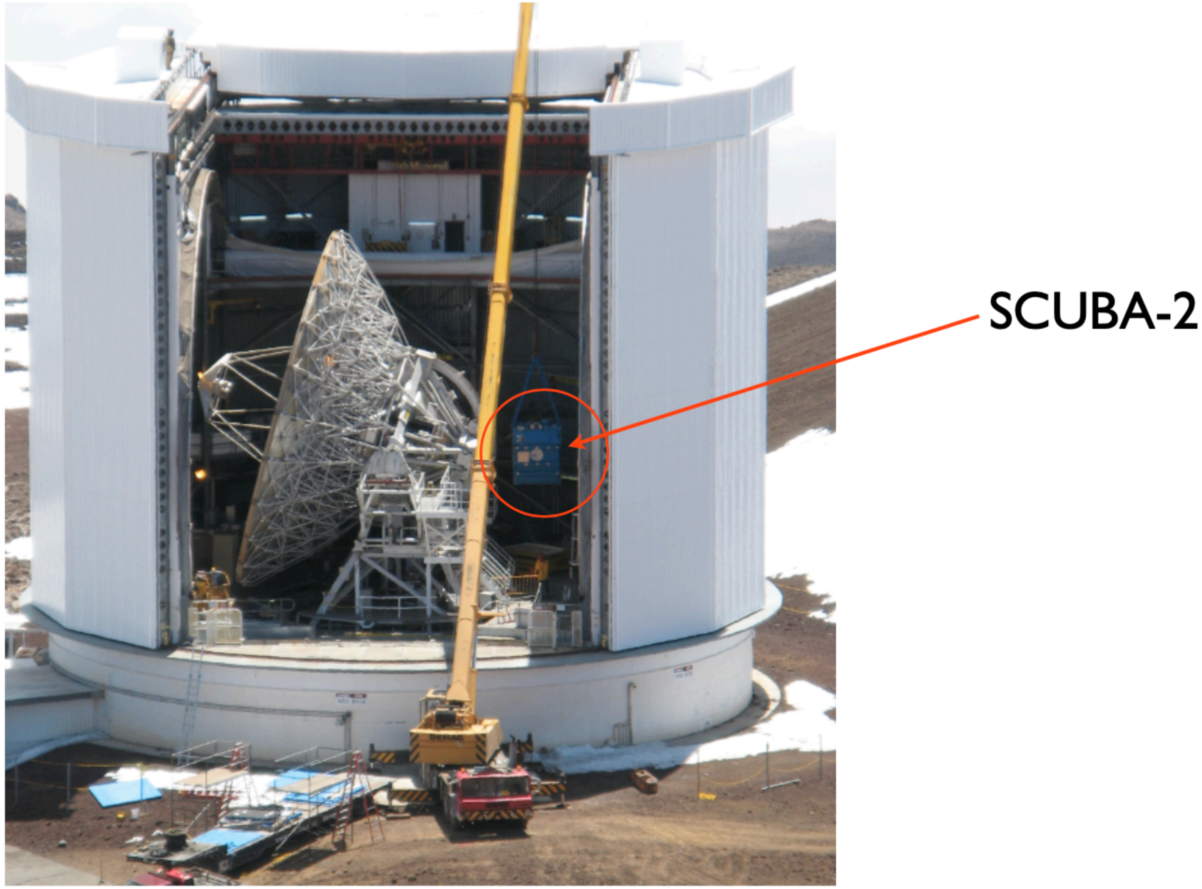
just 2 keywords here:

– Hot Electron Bolometers (HEB): incoming radiation onto some metal compounds (e.g. NbN) heat preferentially the electron gas → Te locally rises and pushes NbN out of superconductivity → elevated resistivity → signal detection

– Transition-Edge-Sensors (TES): exploits the strongly temperature-dependent resistance of the superconducting phase transition

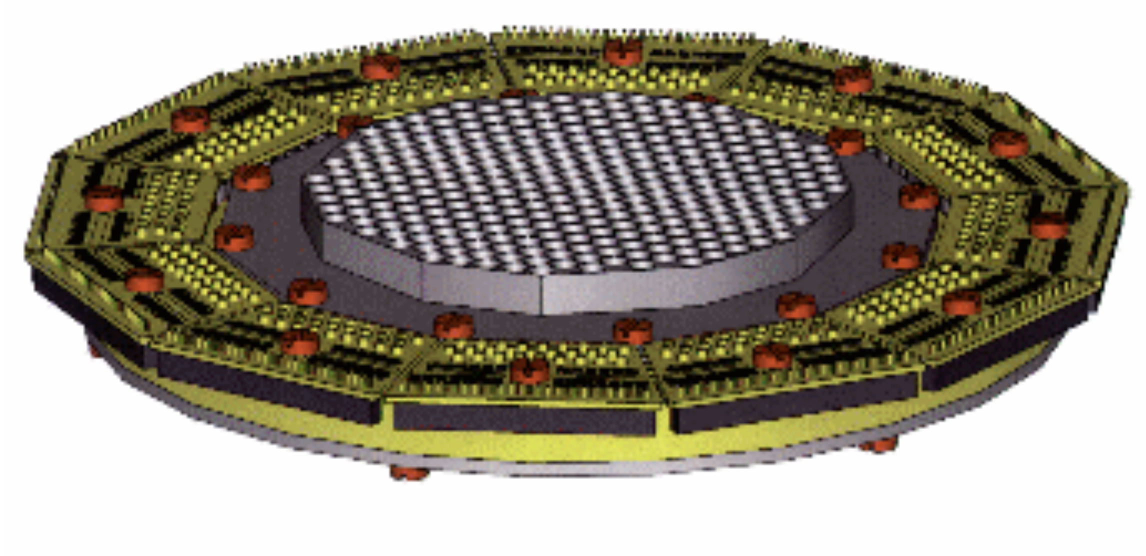
Bolometers: Scuba / Scuba-2

Bolometers started out with a single detecting element and imaging was performed by a raster process in which telescope moves over a celestial object one pixel at a time! Now, bolometer arrays have been constructed greatly improving survey speed.



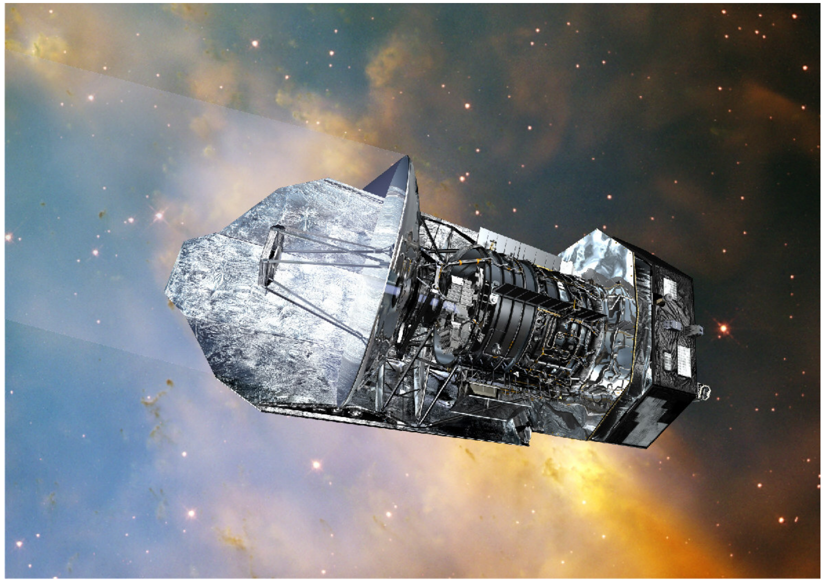
Bolometer: LABOCA

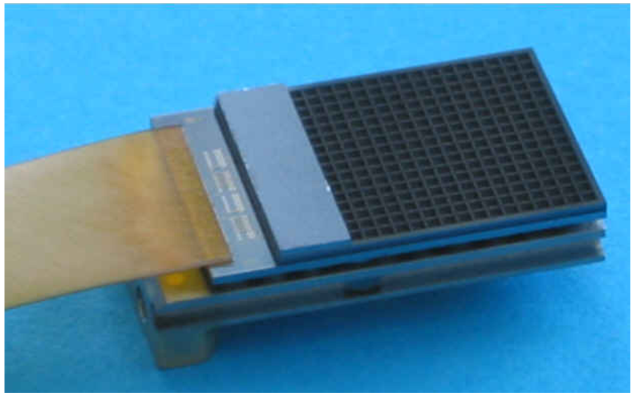
– Operates at 870 μm (345 GHz) with ~60 GHz of bandwidth
– Each of the 295 elements collects a signal within a beam size of 19.2 arcsec
– pixel distance: ~36 arcsec, Total field-of-view on the sky: 11.4 arcmin diameter

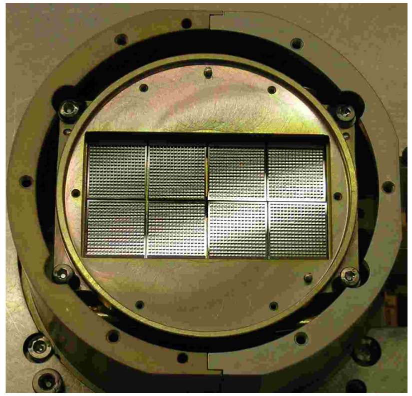


Bolometer: PACS @ Herschel

first time to build astronomical bolometers down to 60 μm
– 64x32 bolometer pixels array at “blue” side (60-130 μm),
  32x16 pixels at “red” side (130-210 μm)
– bolometers closely packed, they over-sample the beam, no beam feed horns





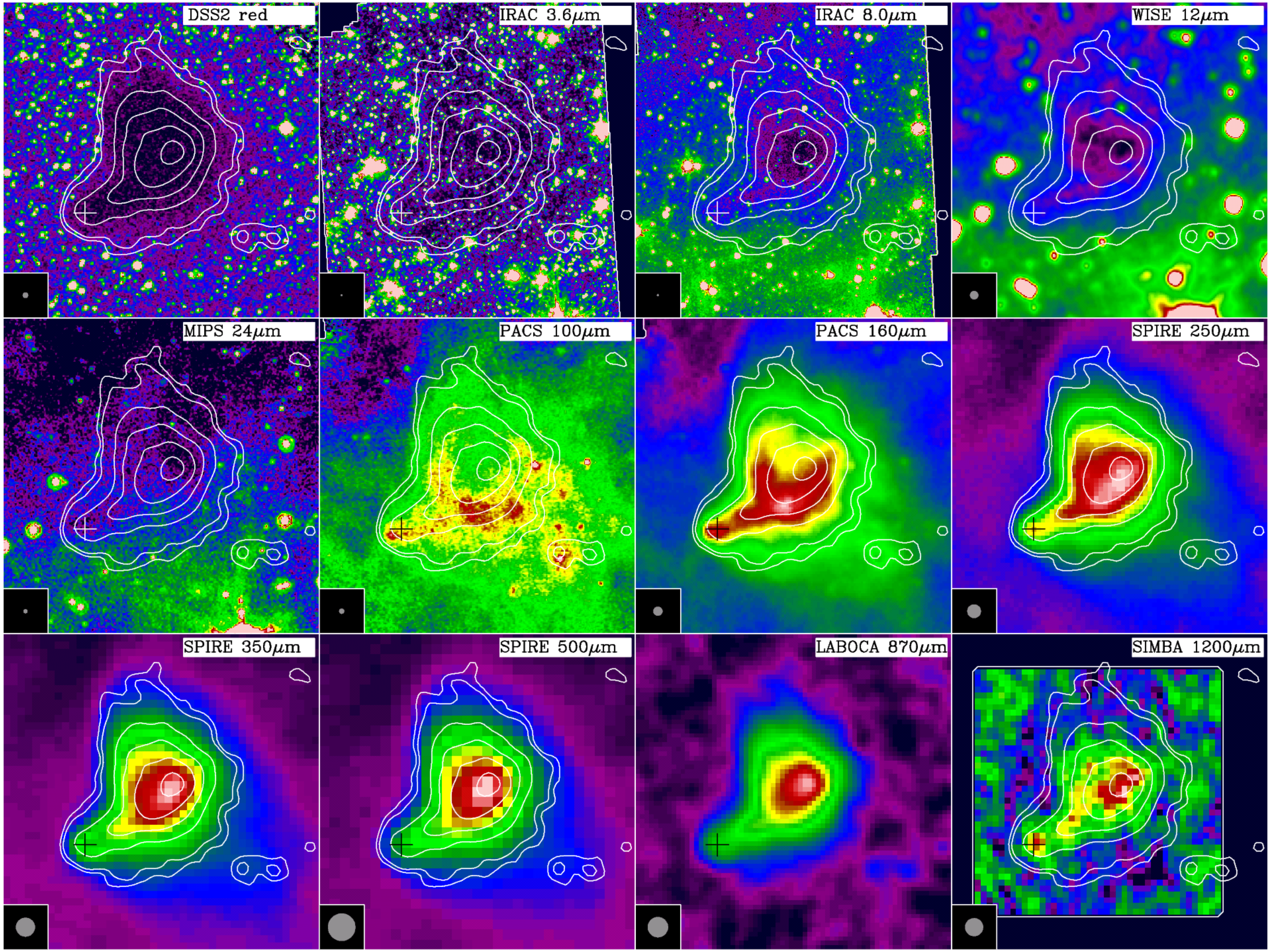


One 16x16 pixel sub-matrix of PACS & the 4x2 sub-matrix composite of PACS-blue (l = 60 – 120 μm)

built at CEA Saclay (France).

Bolometer: Application example

starless globule B 68 in Ophiuchus



Nielbock et al. 2012