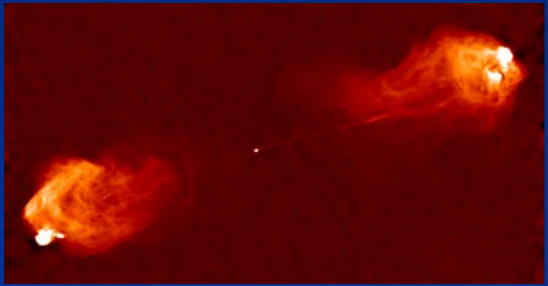
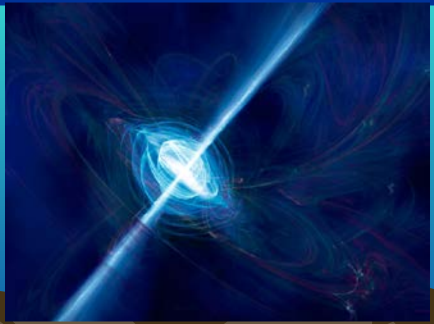
Radio Astronomy

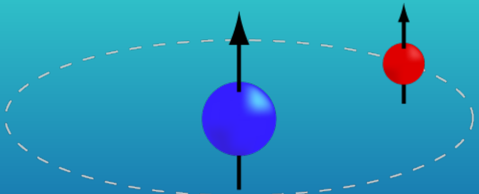
PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

An elective lecture course for the winter term 2012/13 at the Ruperto Carola University Heidelberg







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Tentative Schedule:
16.10. Introduction and overview (HL & HB)
23.10. Emission mechanisms, physics of radiation (HB)
30.10. Telescopes – single-dish (HL)
06.11. Telescopes – interferometers (HB)
13.11. Instruments – continuum detection (HL)
20.11. Instruments – line detection (HB)
27.11. Continuous radiation (free-free, synchrotron, dust, CMB) (HL)
04.12. Line radiation (HB)
11.12. Radiation transfer (HL)
18.12. Buffer ...
08.01. Molecules and chemistry (HL)
15.01. Physics and kinematics (HB)
22.01. Applications (HL)
29.01. Applications (HB)
05.02. Exam week

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<u>Topics for today:</u>

- recap on beams and image convolution
- continuum detection in the (sub-)mm: Bolometers
- Receivers in the mm and cm range (starting)

Apparent and real intensity distributions

The imaging (or mapping) process unavoidably alters the original intensity distribution that we want to study on the sky:

Happens for both the single-dish and the interferometric observations

A common qualitative description can be found:

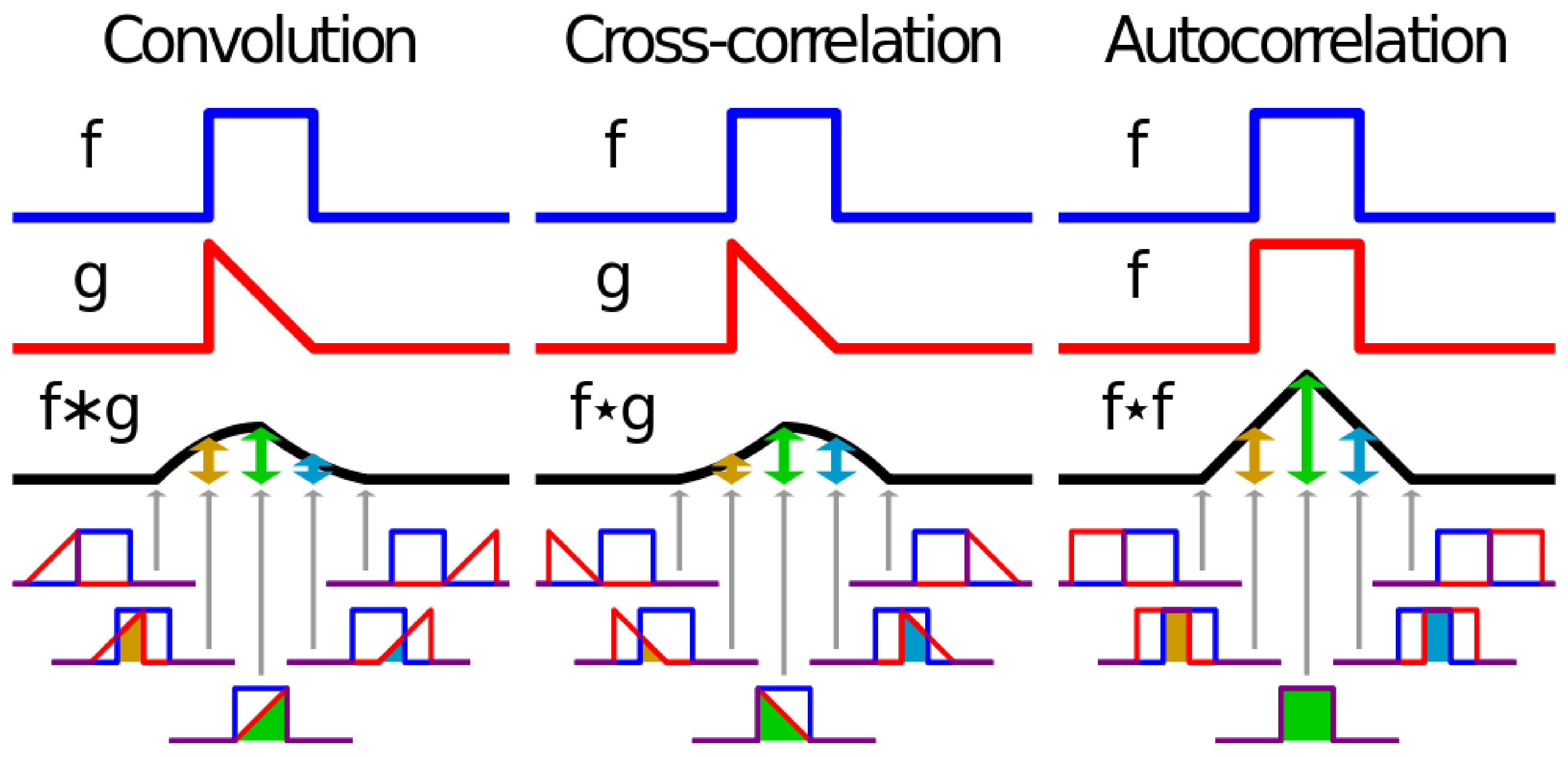
B_{meas} = Apparatus-Function x B_{orig}

↓ ↓

Point-Spread-Function Convolution

Single-dish telescope:	PSF is the telescope (power) pattern – the “beam”
Interferometer:	PSF is the “dirty beam”, i.e., the Fourier Transform of the interferometer geometric sampling function

A simple pictorial summary on convolutions and correlations



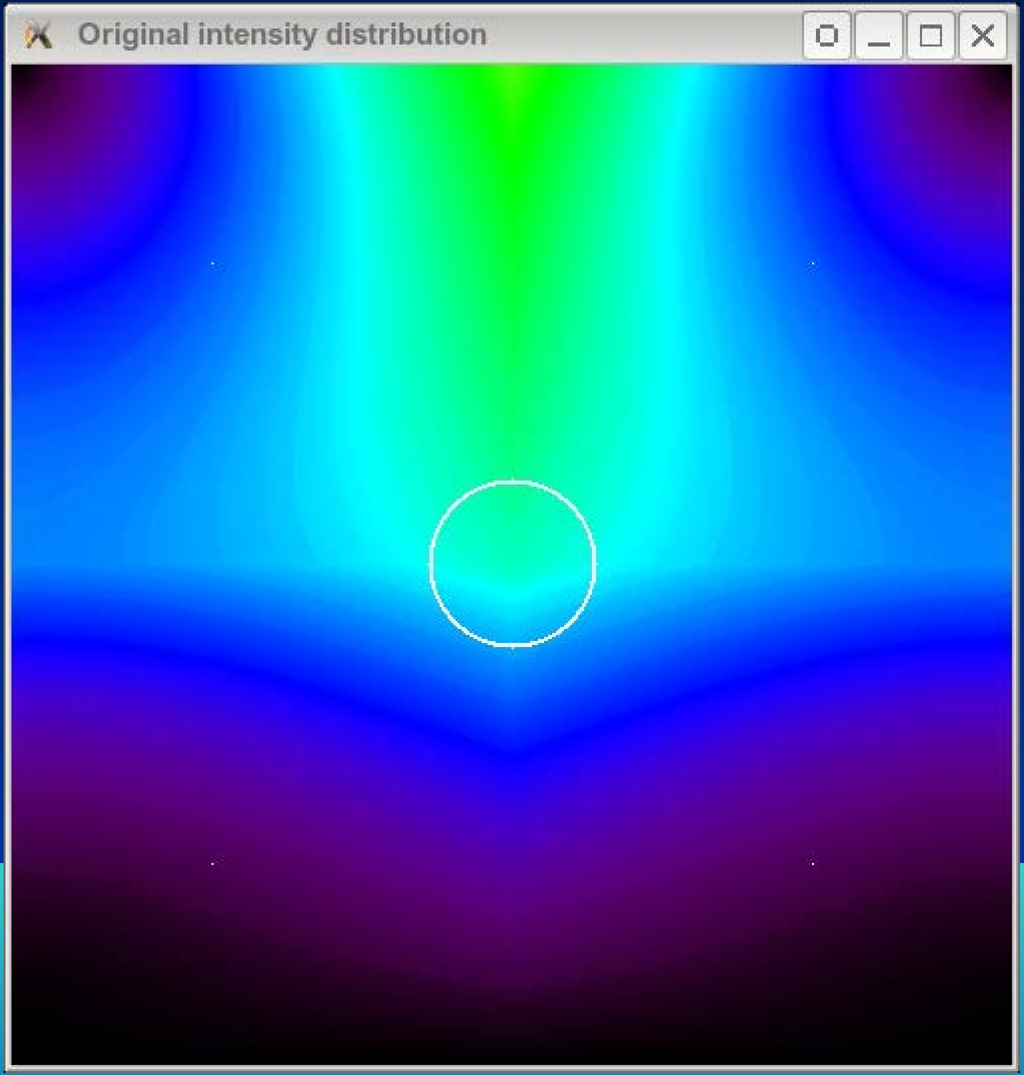
Source: Wikipedia (credit where credit is due ...)

Convolution: “Faltung” in German (i.e., folding) → mirror-folding of one of the functions before combination

Standard book on Fourier transforms and many issues related to such operations:

Bracewell, R.N., The Fourier Transform and Its Applications (McGraw-Hill, 1965, 2nd ed. 1978, revised 1986)

Convolution with a beam profile



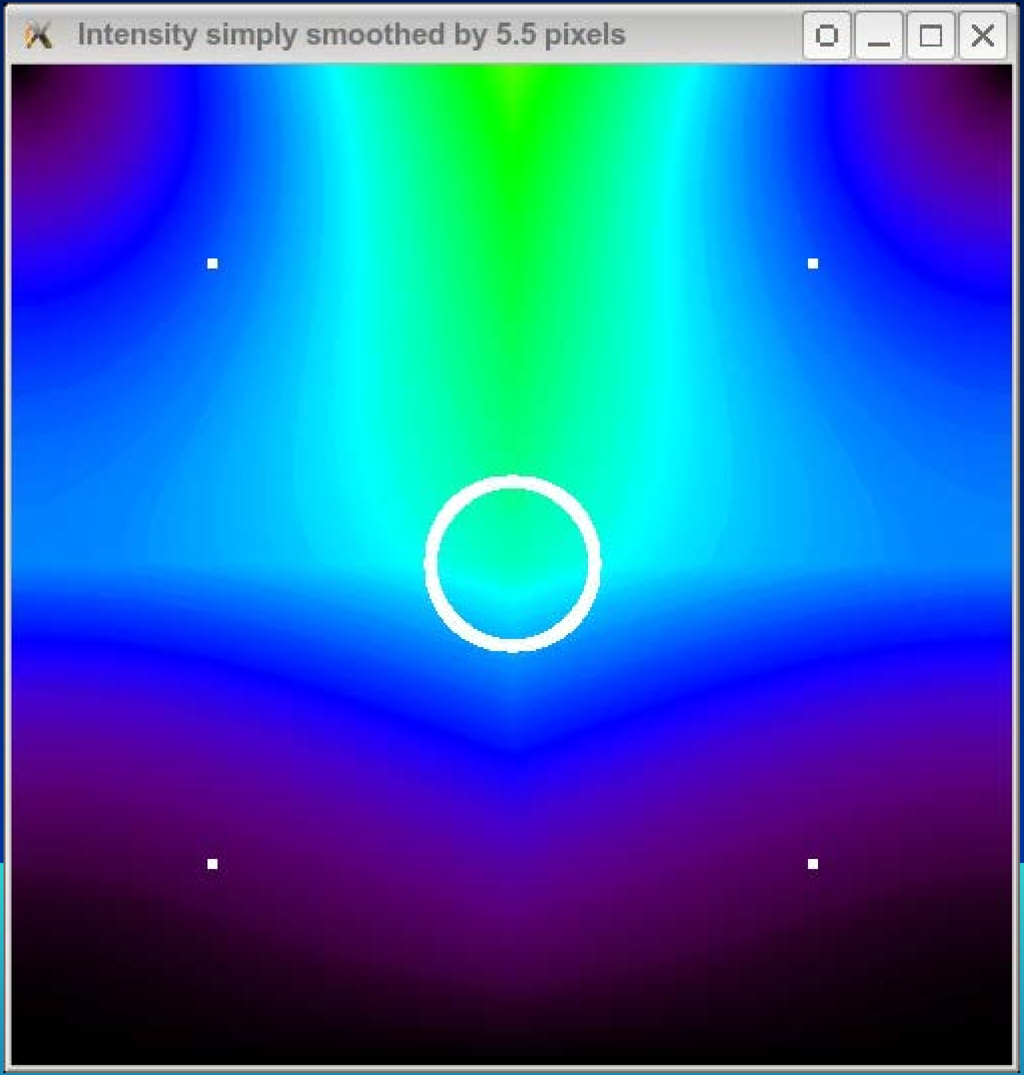
Original intensity distribution
(in super-resolution)

Smoothly modulated extended background

+ 4 strong point sources
(intensities differing by √10)

+ bright thin ring

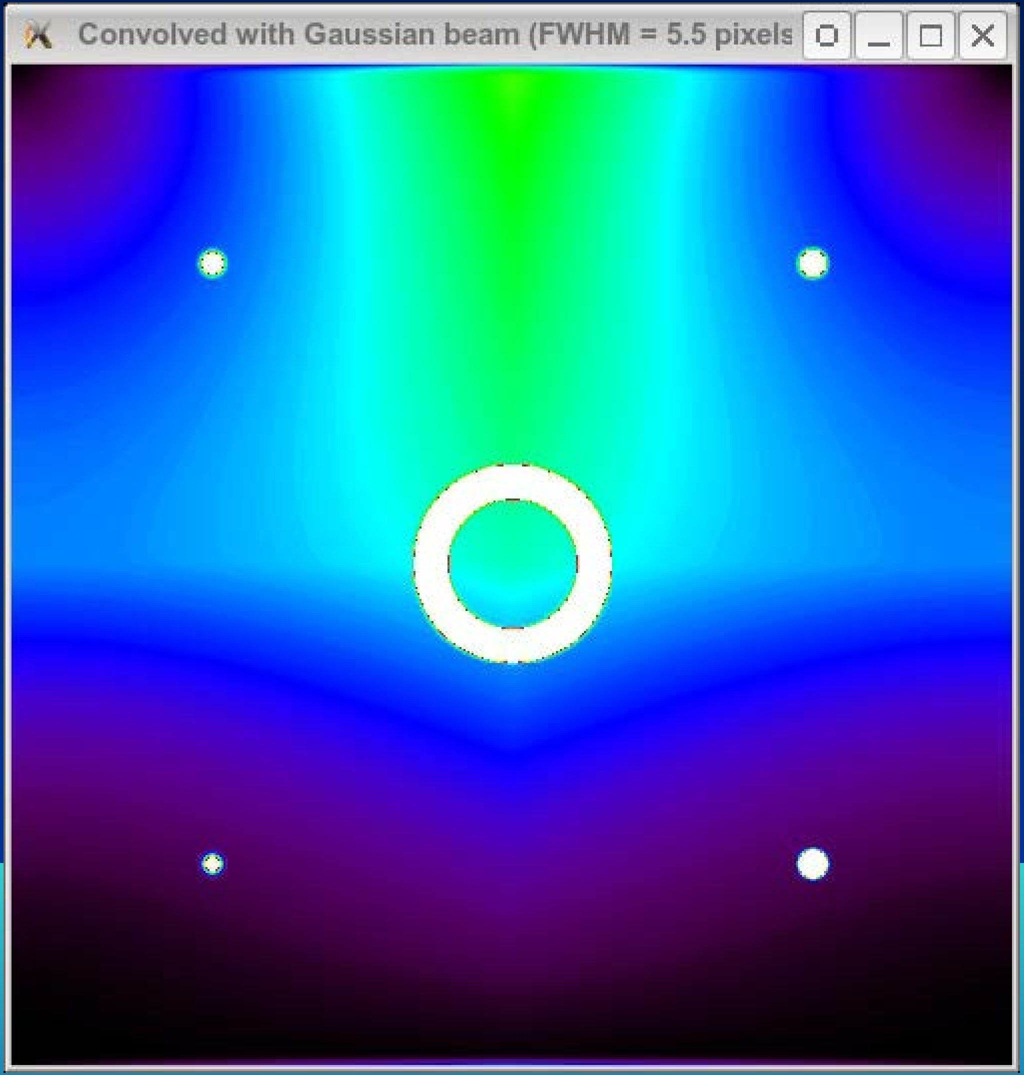
Convolution with a beam profile



Intensity distribution after simple SMOOTHING by 5.5 pixels (“running boxcar” smoothing, just acts locally)

But the real imaging process is not that simple!

Convolution with a beam profile

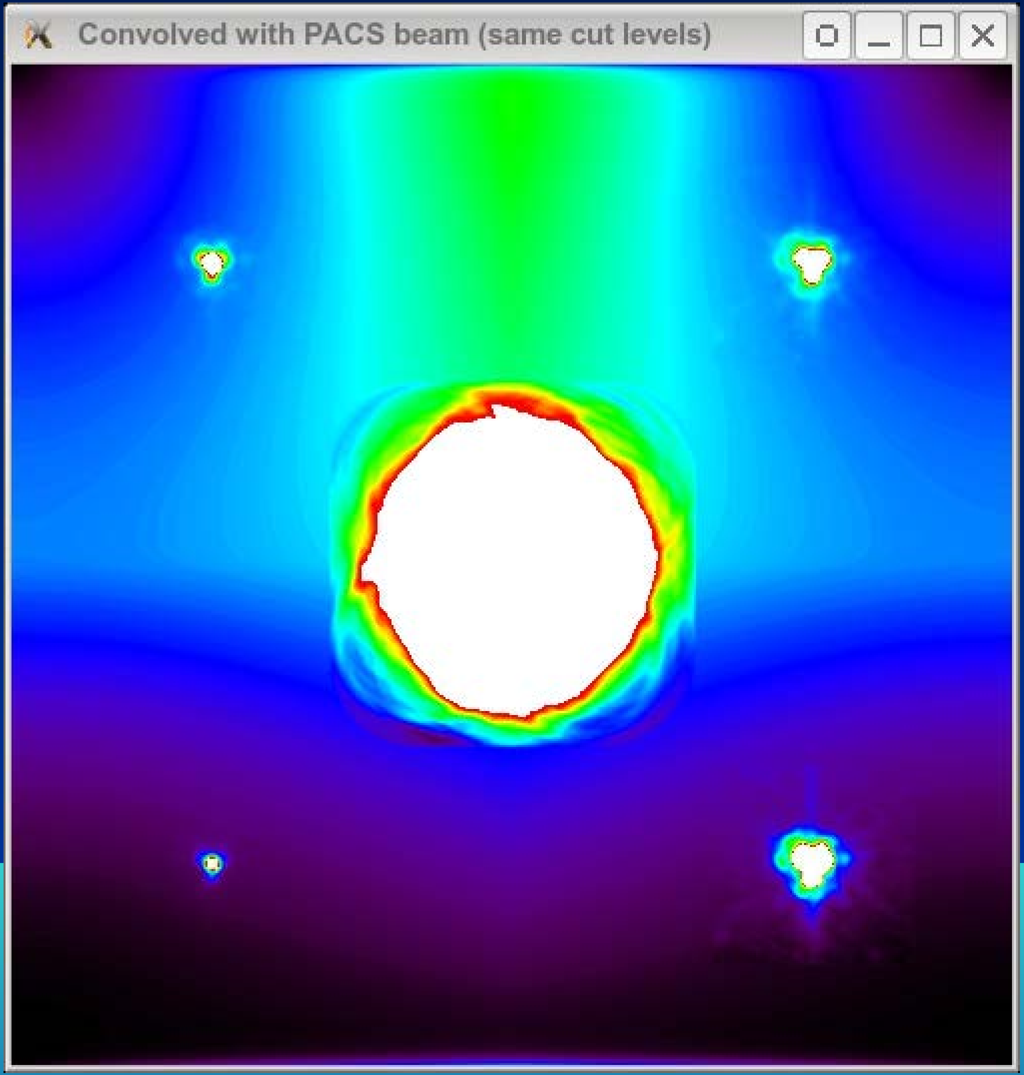


CONVOLUTION of the original intensity distribution with a Gaussian beam profile with a Full Width Half Maximum (FWHM) of 5.5 pixels

Point sources → Gaussian profiles

Ring thickens as well

Convolution with a beam profile

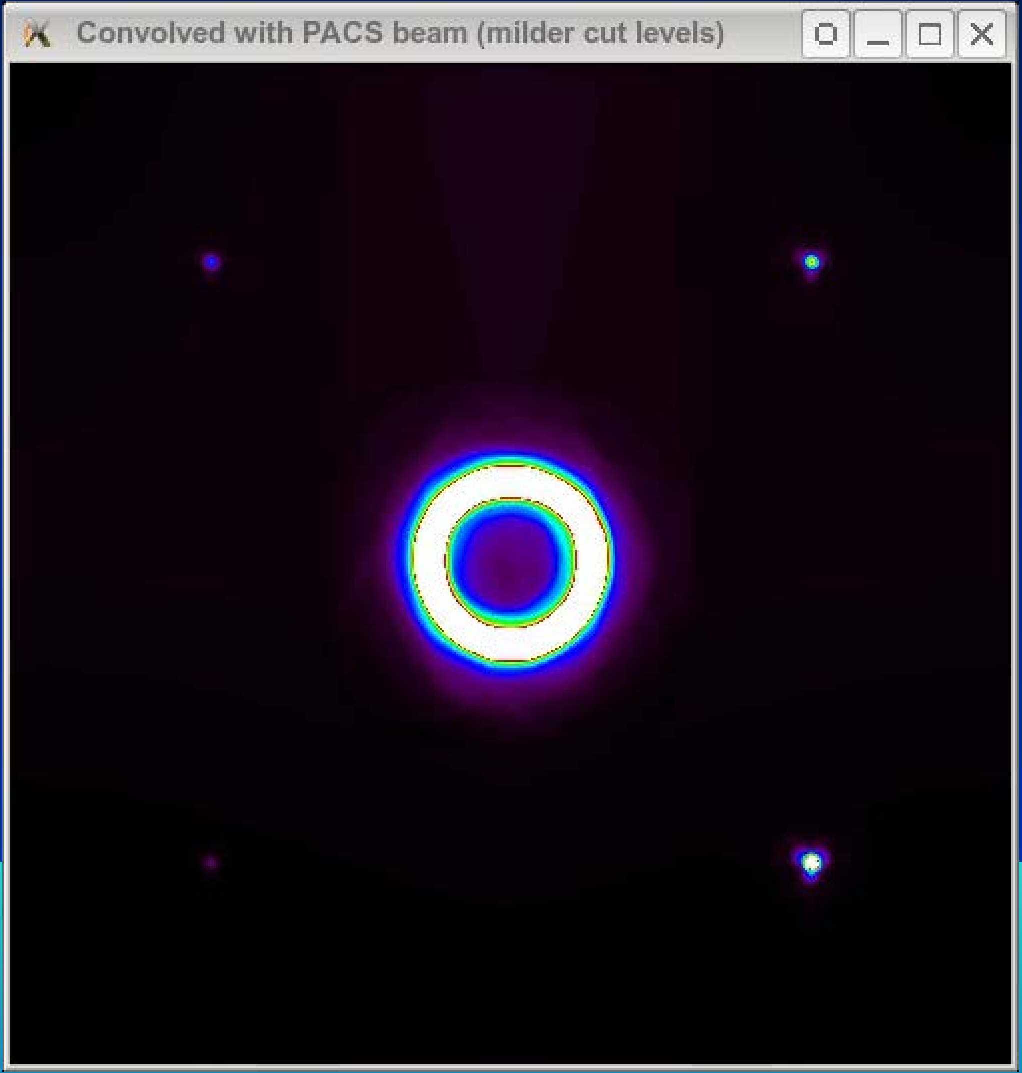


CONVOLUTION of the original intensity distribution with a real beam profile with lots of internal structure :
Here: the beam profile of the PACS instrument aboard the Herschel Satellite
(Gaussian fit to this profile also has as FWHM of 5.5 pixels)

Point sources → copies of the beam profiles

More intensity around the ring smeared out

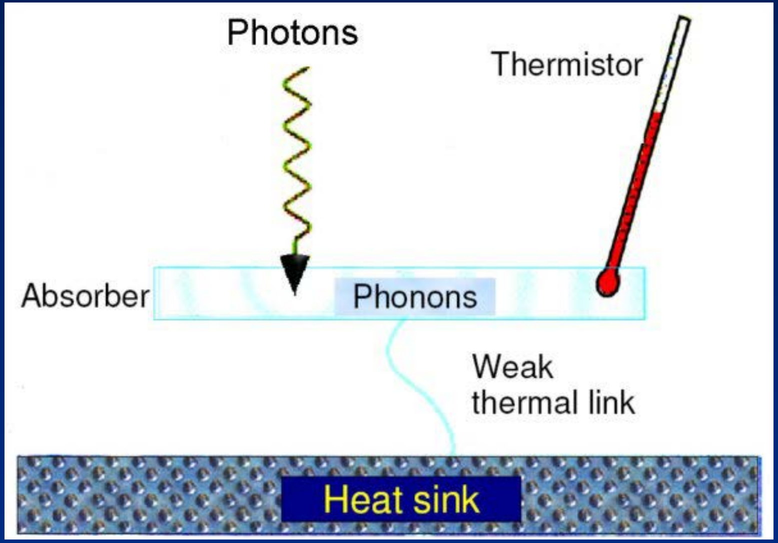
Convolution with a beam profile



CONVOLUTION of the original intensity distribution with a real beam profile with lots of internal structure :
Here: the beam profile of the PACS instrument aboard the Herschel Satellite
(Gaussian fit to this profile also has as FWHM of 5.5 pixels)

This is the same result as shown before, but now with milder intensity cut levels.

Continuum radiation detection in the (sub-)mm range: Bolometers – Incoherent receivers



Bolometers as very sensitive thermometers

Composite of an absorber and the actual thermometer (thermistor)

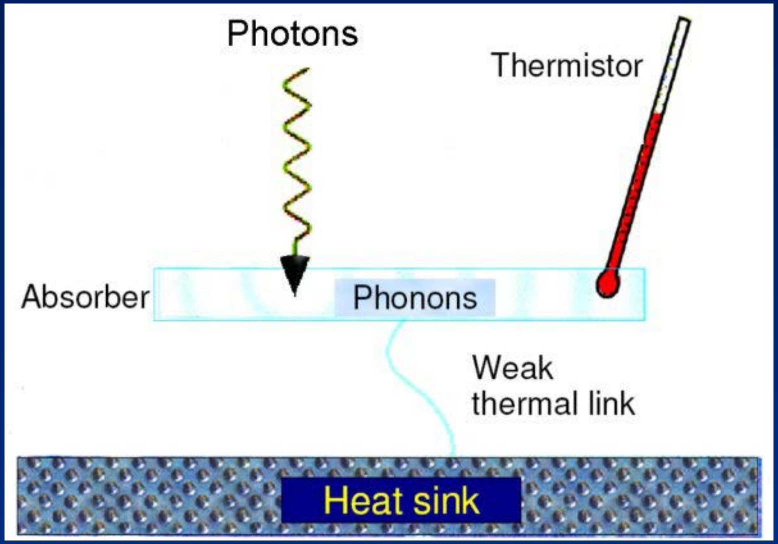
The absorber is kept at very low temperature (0.3 degree above absolute zero) by a weak thermal link to a heat sink.

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.

Continuum radiation detection in the (sub-)mm range: Bolometers – Incoherent receivers



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

→ at longer wavelength: photons deposit less and less energy into the absorber material

On the other hand: bolometers as such are not strongly discriminating regarding the spectral range of the incoming radiation

→ **(n)** spectral range (pre-)selection by means of feed horns and filters necessary

→ **(+)** wide spectral bandwidth input easily possible – helps to achieve sufficient SNR (signal-to-noise)

Continuum radiation detection in the (sub-)mm range: 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

Further complication:
→ **(–)** 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 ↔ ^{4}He gets superfluid at ~2 K :-(
Hence: use ^{3}He instead … does not become superfluid, but is much more rare

High-Tech involved to push the devices to better and better sensitivity – just 2 keywords here:

- Hot Electron Bolometers (HEB): incoming radiation onto some metal compounds (e.g. NbN) heat preferentially the electron gas → T_e locally rises and pushes T_{NbN} out of superconductivity → elevated resistivity → signal detection
- Transition-Edge-Sensors (TES): exploits the strongly temperature-dependent resistance of the superconducting phase transition

Continuum radiation detection in the (sub-)mm range: Bolometers

Some examples for previous (and current) bolometer arrays with modest sizes in astronomy:

- **SCUBA** @ JCMT 15-m telescope on Mauna Kea (Hawaii): 91-element array (working at 850 µm) + 37-element array (working at 450 µm), 1997 – 2005

- **SIMBA** @ SEST 15-m telescope on La Silla (Chile): 37-element array, working at 250 GHz (1.2 mm wavelength), 2001 – 2003

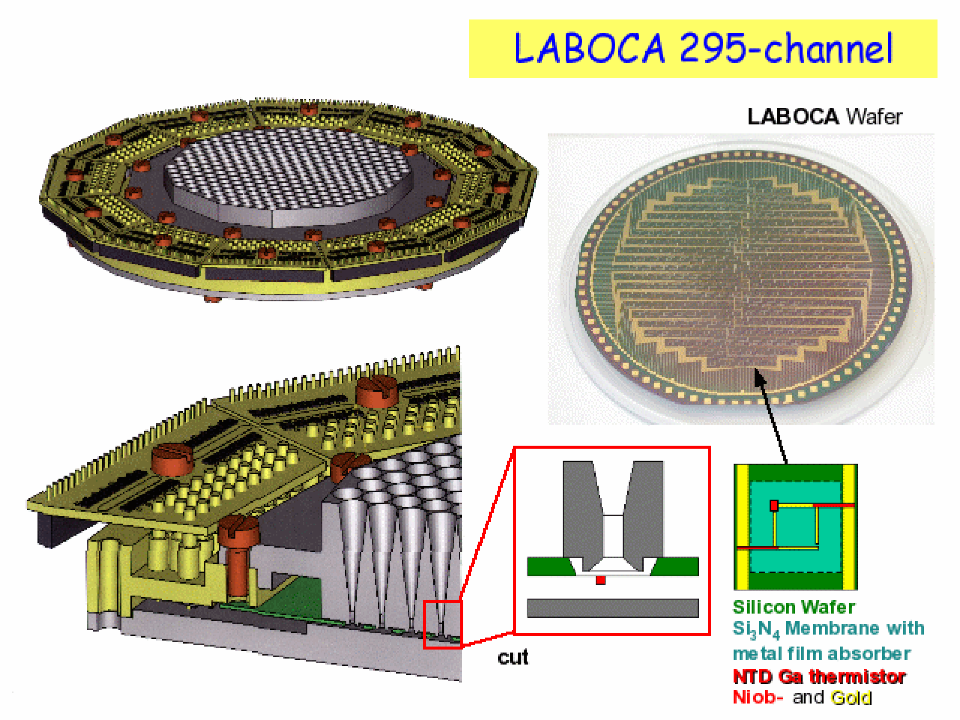
- **MAMBO** @ IRAM 30-m telescope in the Sierra Nevada (Spain): 118-element array, working at 250 GHz (1.2 mm wavelength), 1999 – 2011

- **MUSTANG** @ GBT 110-m telescope in West Virginia (USA): 64-element array, working at 90 GHz (3.3 mm), 2009 and ongoing

Bolometer examples (I): LABOCA @ APEX
***L**arge **A**pex **BO**lometer **CA**mera*

http://www3.mpifr-bonn.mpg.de/staff/gsiringo/laboca/laboca_at_the_mpifr_bolometer_group.html

APEX 12-m telescope



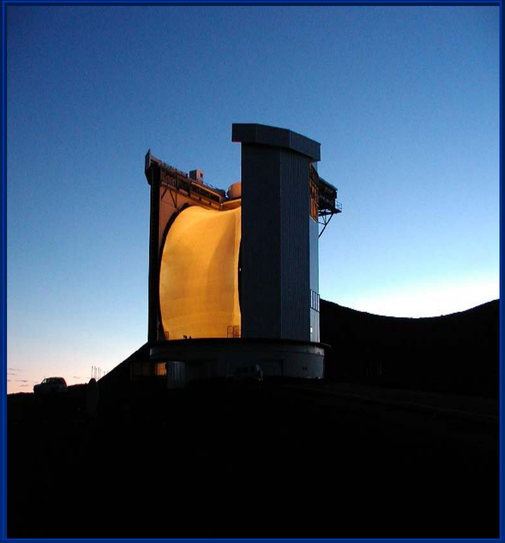
**LABOCA 295-element array,
in operation since 2006/2007,
Built by MPIfR Bonn (Germany)**

**NTD: Neutron-transmutation-doped
Metal film absorber made of Titanium**

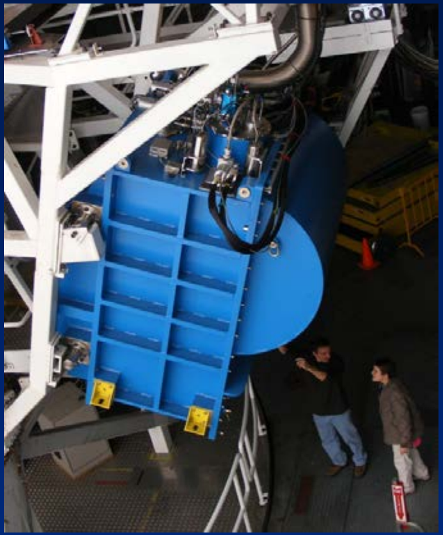
– Operates at 870 µm (345 GHz) with ~60 GHz of bandwidth
– Each of the 295 elements collects a signal within a beam size of 19.2 arcsec
– pixel distance: ~36 arcsec, Total field-of-view on the sky: 11.4 arcmin diameter

→ nearly the only ground-based bolometer camera to cover the southern sky
→ one prime result so far: ATLASGAL – mapping of the (southern) Galactic plane (project led by MPIfR Bonn)

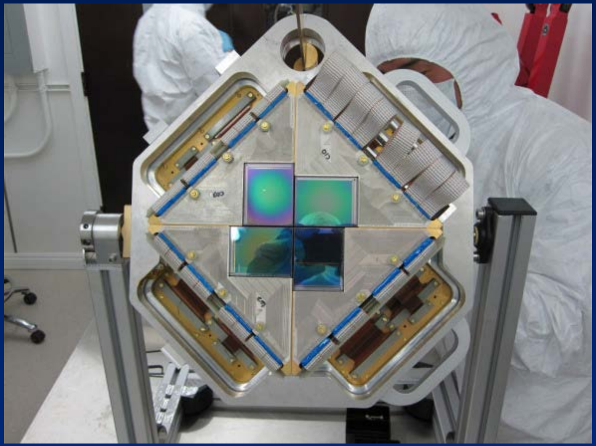
Bolometer examples (II): SCUBA-2 @ JCMT
Submillimetre Common-User Bolometer Array



JCMT 15-m telescope



SCUBA-2, weighting ~4.5 tons



Look onto the four bolometer sub-arrays of one of the two wavelength ranges employed

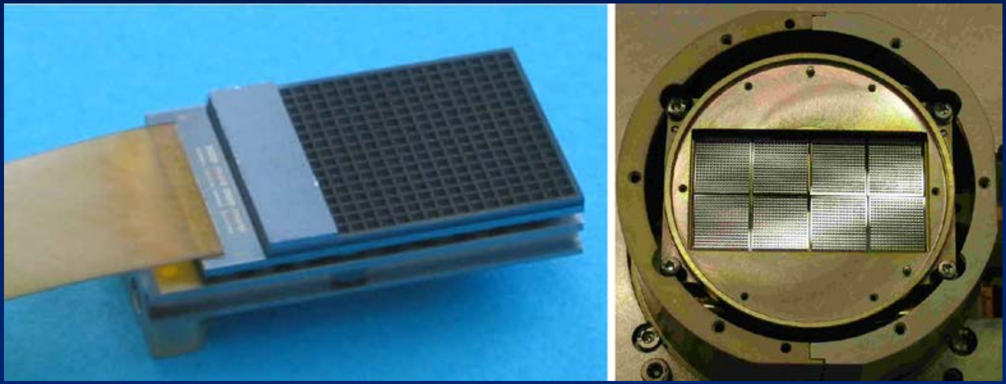
- Transition-edge-sensors (TES), multiplexed by Superconducting Quantum Interference devices (SQUIDs); development by NIST (USA)
- four 32x40 detector arrays at each of 850 and 450 micron
- 850 µm bolometers packed with beam/2 spacing, 450 µm ones with beam/1

→ One of the last promises for the JCMT; better sensitivity and much higher mapping efficiency than SCUBA-1

→ But: long delays … and, given a certain planned speed of sky coverage, then sensitivity will not be as high as expected … :-(

Bolometer examples (III): PACS @ Herschel satellite
Photodetector Array Camera and Spectrometer

The Herschel Satellite by ESA with its 3.5-m mirror

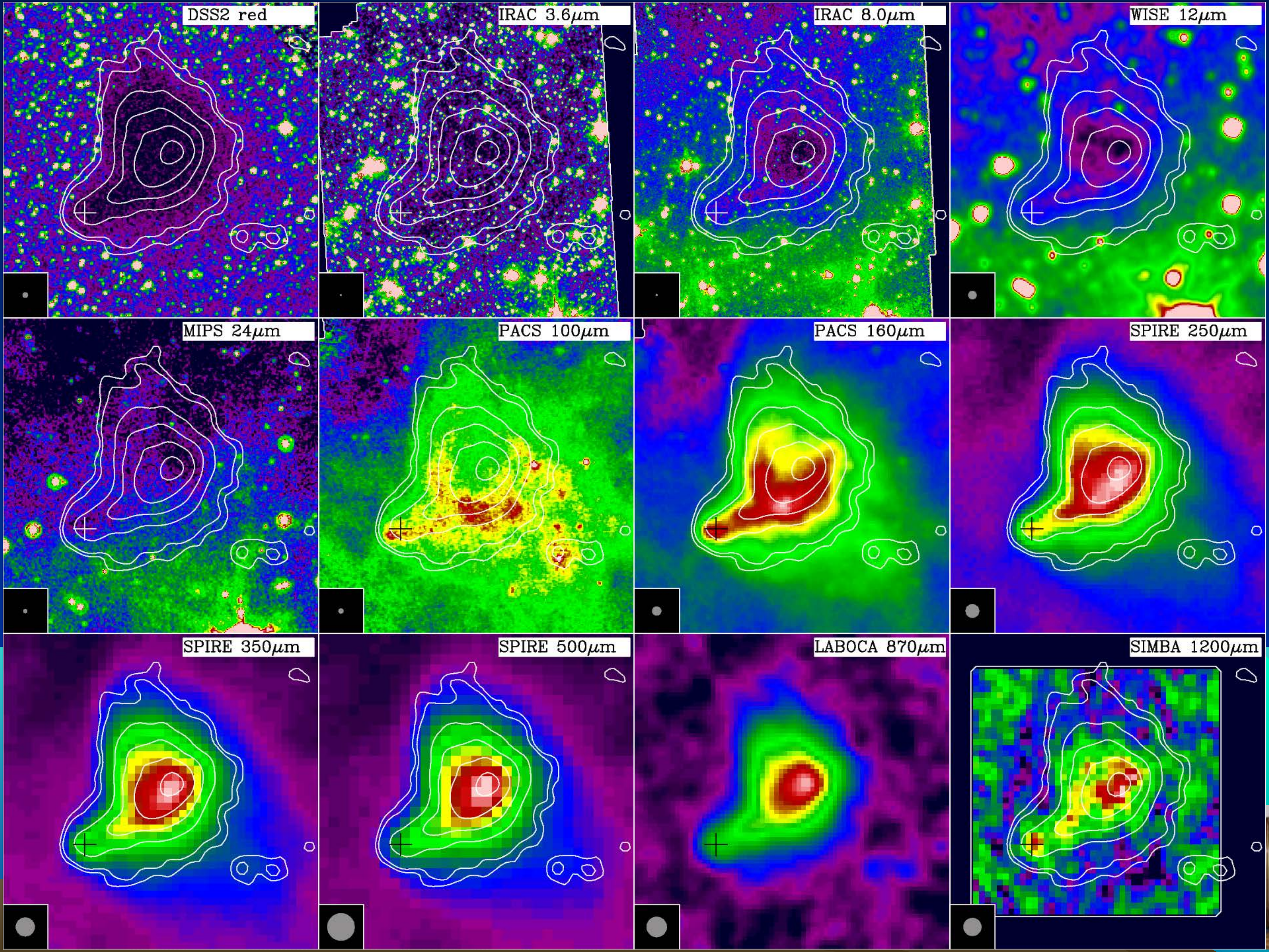


One 16x16 pixel sub-matrix of PACS & the 4x2 sub-matrix composite of PACS-blue (λ = 60 – 120 µm)
The PACS bolometers are built by CEA Saclay (France).

– first time to make astronomical bolometers useful at λs 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

→ In operation since May 2009, satellite will be out of helium in March 2013
→ steep learning curve on how to treat/reduce the raw data coming from the fast-scanning mode of PACS … H. Linz as part of the PACS Instrument Control Center (ICC)

Application example: cold dust emission from the starless globule B 68 in Ophiuchus

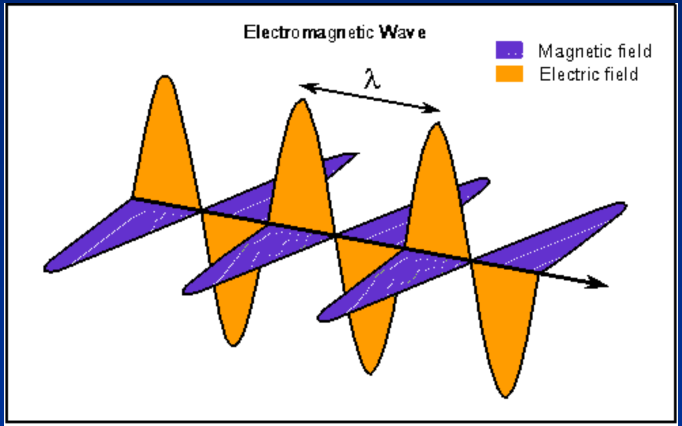


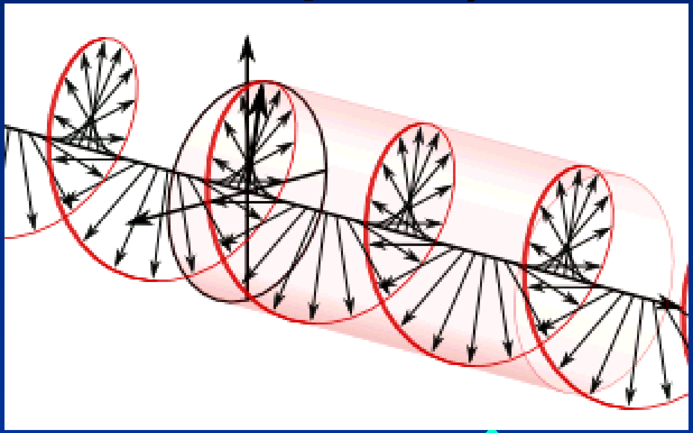
Copyright: Markus Nielbock (MPIA)
Published in : Nielbock et al. (2012), A&A 547, A11
PACS & SPIRE @ Herschel,
LABOCA @ APEX, SIMBA @ SEST
IRAC & MIPS @ Spitzer satellite (These two are not bolometers!)

Receivers at mm and cm wavelengths
Some basics

Keep in mind:

- ***field amplitudes and field phases shall be accessible, not only the intensities!***
- ***electromagnetic waves, in the general case, can come with a preferred polarisation (linear, circular, elliptical)***





Linear polarisation, B and E-Fields shown

Circular polarisation, only E-Field vector shown

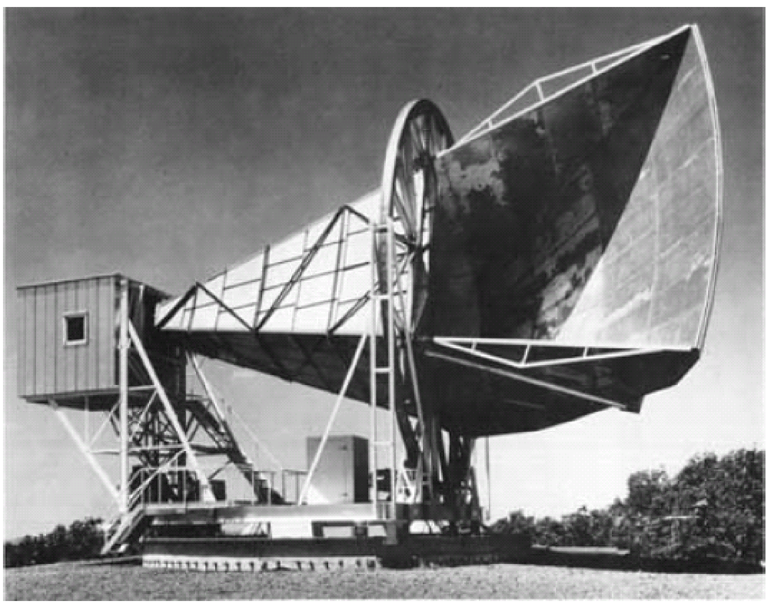
→ If ever possible, we want to retain these qualities during the reception and amplification process

Receivers at mm and cm wavelengths
Some basics

Electromagnetic radiation comes in as waves

→ induces currents in the receivers (feed horns often as the first stage of detection)

→ voltages are being detected which will be amplified and propagated

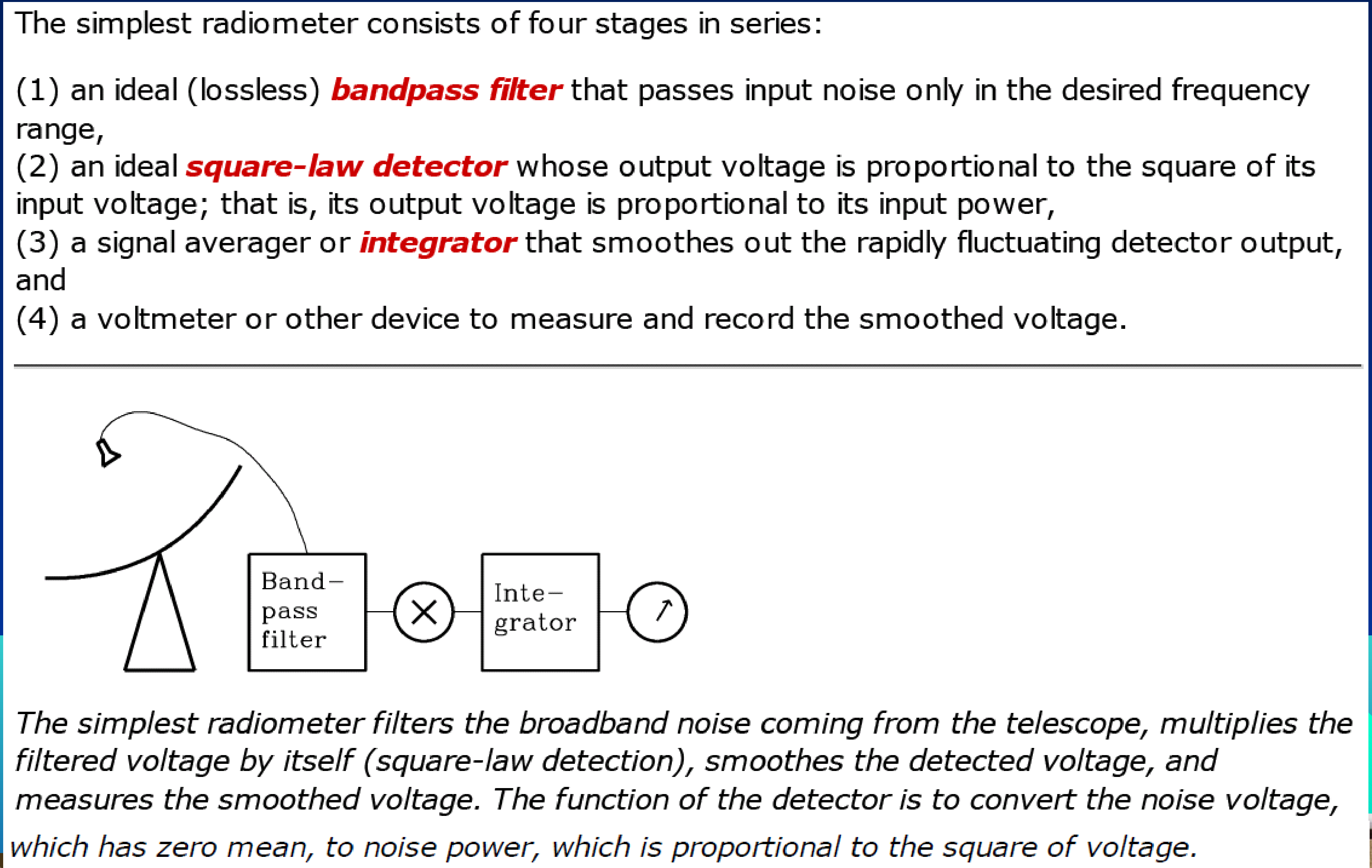


The horn antenna of Penzias & Wilson

Different feed horns in the main dish of a VLA antenna

Receivers at mm and cm wavelengths
Some basics

What follows here is directly adapted from the Condon online lectures: http://www.cv.nrao.edu/course/astr534/ Section 3.E (Radiometers)



The simplest radiometer consists of four stages in series:

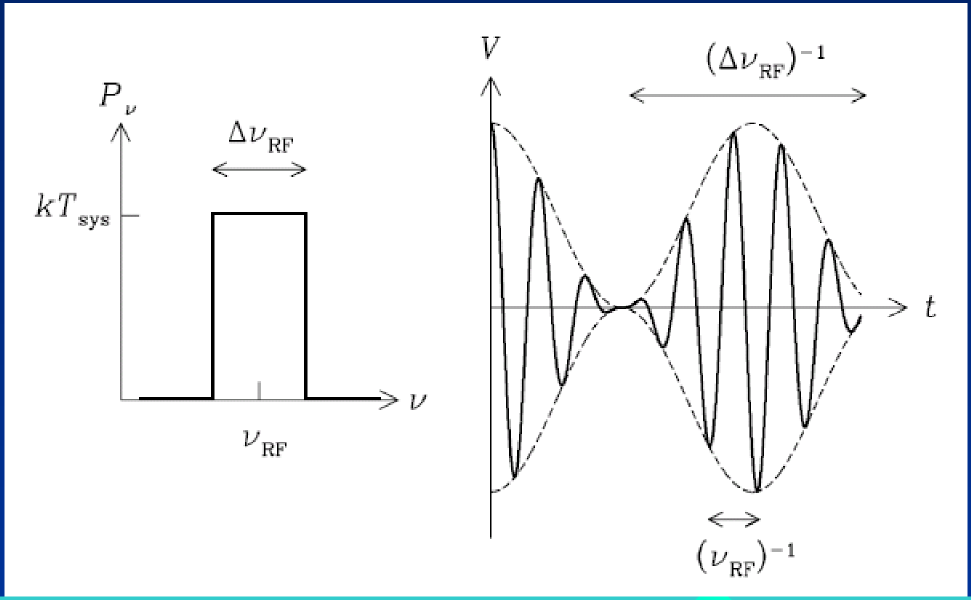
(1) an ideal (lossless) ***bandpass filter*** that passes input noise only in the desired frequency range,
(2) an ideal ***square-law detector*** whose output voltage is proportional to the square of its input voltage; that is, its output voltage is proportional to its input power,
(3) a signal averager or ***integrator*** that smoothes out the rapidly fluctuating detector output, and
(4) a voltmeter or other device to measure and record the smoothed voltage.

The simplest radiometer filters the broadband noise coming from the telescope, multiplies the filtered voltage by itself (square-law detection), smoothes the detected voltage, and measures the smoothed voltage. The function of the detector is to convert the noise voltage, which has zero mean, to noise power, which is proportional to the square of voltage.

Receivers at mm and cm wavelengths
Some basics

Stage 1: The input filter (Note: subscript RF → Radio Frequency)

The receiver in the telescope focus has received lots of different signals (actual noise most of the time, but also the astronomical source, which in the following will also be put in the mix as another source of noise.)



The receiver delivers input voltages to the input filter. The voltages carry a certain spectral power [Watts]. The filter just transmits signals from a certain frequency range.

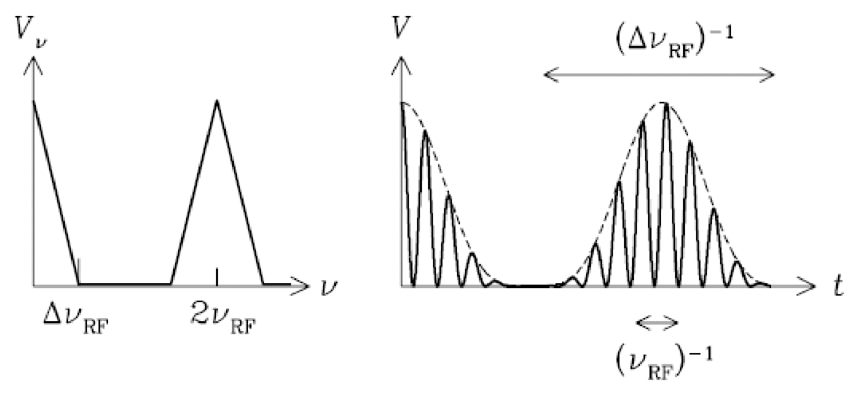
Remember Fourier relation between time- and frequency domain! That also means, that a rectangular filter in frequency (from $\nu_{RF} - ½ \Delta\nu_{RF}$ to $\nu_{RF} + ½ \Delta\nu_{RF}$) transforms to a sinusoidal envelope modulation (with a frequency $\Delta\nu_{RF}$) on top of the high-frequency signal of the voltages themselves (coming with ν_{RF}).

Receivers at mm and cm wavelengths
Some basics

Stage 2: The square-law detector

The filtered voltage is multiplied by itself ("squared"). The output voltage is proportional to the square of the input voltage. Hence, the output is proportional to the input power. $V_{out} \sim P_{in}$

For an input voltage $V_\mathrm{i} \approx \cos(2\pi\nu_\mathrm{RF})$ the output voltage is something like $V_\mathrm{o} \propto \cos^2(2\pi\nu_\mathrm{RF})$. This relation can be rewritten as $[1 + \cos(4\pi\nu_\mathrm{RF})]/2$ using the common double-angle formula. This function's mean value equals the average power of the input signal.



The high-frequency fluctuations (now with $2\nu_{RF}$) contain no useful information about the source and will be filtered out in the next stage.

Receivers at mm and cm wavelengths
Some basics

Stage 3: The integrator

Both the rapidly varying component at frequencies near $2\nu_{RF}$ and its envelope vary on time scales that are normally much shorter than the time scales on which the average signal power ΔT varies. The unwanted rapid variations can be suppressed by taking the arithmetic mean of the detected envelope over some time scale $\tau >> 1/(\Delta\nu_{RF})$ by integrating or averaging the detector output.

This integration might be done electronically by smoothing with an RC (resistance plus capacitance) filter or by numerically by sampling and digitizing the detector output voltage and then computing its running mean.

Receivers at mm and cm wavelengths
Some basics

Things to keep in mind for Stage 3:

Due to the “squared” treatment, all voltages are positive now, hence further averaging in time will always give a positive signal. The mean of this averaged signal is proportional to the input power.

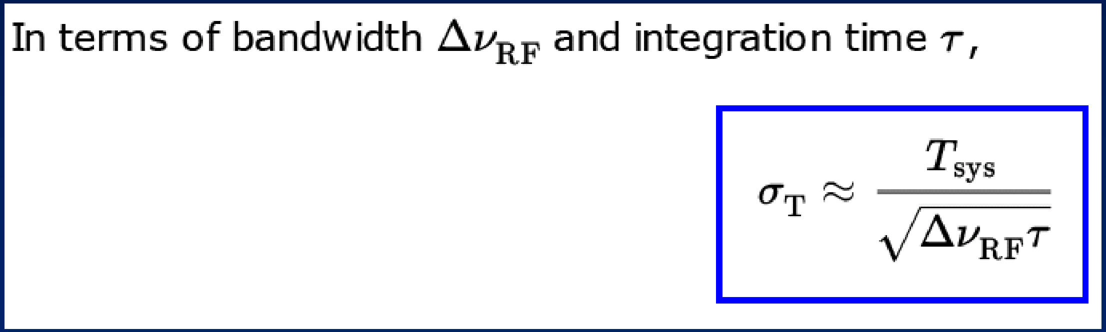
The width of the slower-varying envelope is proportional to the inverse of the filter width $1/(\Delta\nu_{RF})$ applied at Stage 1 (see also the graphs on the previous 2 slides). Thus, it gets obvious that for a given integration time τ one can place more copies of this envelope variation (i.e., more samples of it) within this time span τ , the wider the original filter width $\Delta\nu_{RF}$ was.

In the time interval τ there are hence $N=(2\Delta\nu_{RF}\tau)$ independent samples of the total noise power T_{sys}, each of which has an rms error $\sigma_T \sim \mathrm{sqrt}(2)\ T_{sys}$. The rms error in the average of N>>1 independent samples is reduced by the factor sqrt(N), so the rms receiver output fluctuation is then only:

$$\sigma_T = \mathrm{sqrt}(2)\ T_{sys} / \mathrm{sqrt}(N)$$

Receivers at mm and cm wavelengths
Some basics

Ideal radiometer equation:

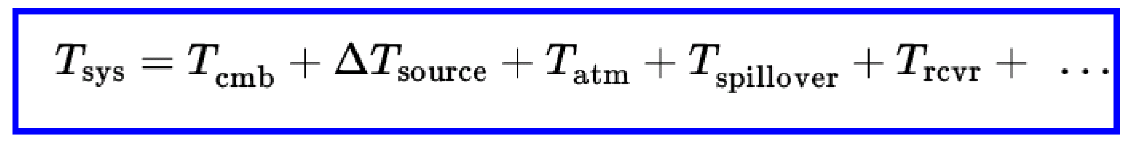


In terms of bandwidth $\Delta\nu_{\mathrm{RF}}$ and integration time τ,

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

σ_T as the resulting r.m.s. receiver output fluctuations

Note that T_{sys} is a combination of many terms related to the antenna and the receiver:



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

T_{CMB} = 2.73 K, T_{atm} from atmospheric emission within telescope beam, T_{spill} as signal noise that the receivers pick up beyond the main reflector, T_{rcvr}: represents the noise power created by the receiver itself (electronics etc.)

Note: noise input due to the source itself ΔT_{source} is very small compared to T_{sys} ! But ΔT_{source} doesn't have to beat the system temperature, but just be at least 3 – 5 times stronger than the fluctuations σ_T !

e.g., sky survey at 4.85 GHz (~ 6cm) with the (later broken-down) 300-foot telescope:

T_{sys} ~ 60 K, but ΔT_{source} ~ 0.01 K on average

The Antenna Temperature

Remember the effective area A_e of a telescope and its relation to the beam solid angle Ω_A : $A_e\,\Omega_A = \lambda^2$

An antenna (with A_e) with the normalised power pattern $P_n(\theta,\varphi)$, pointed at a brightness distribution $B_\nu(\theta,\varphi)$ on the sky, will deliver as output a total power per unit spectral bandwidth of:

$$W = \tfrac{1}{2} A_e \iint B_\nu(\theta,\varphi)\; P_n(\theta,\varphi)\, d\Omega$$

Assume Rayleigh-Jeans limit ($h\nu \ll k_b T$) and assign a temperature to this power:

$W = k_b\, T_A$ ↔ **antenna temperature T_A**

The Antenna Temperature

Remember the effective area A_e of a telescope and its relation to the beam solid angle Ω_A : $A_e\ \Omega_A = \lambda^2$

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$W = k_b\ T_A$ ↔ **antenna temperature T_A**

We can go back and employ the antenna solid angle Ω_A instead of A_e and remember that Ω_A is the integral over the normalised beam pattern P_n.

Use the concept, that instead of the full intensity distribution B_ν (with units [$W / m^2 / Hz / sr$]) one often uses just an equivalent temperature (in Kelvin] derived from the Rayleigh-Jeans variety of the Planck-Function:

$$B_{RJ} = 2\,\nu^2 / c^2 \;\; k_b T \qquad \leftrightarrow \qquad T_b \;=\; B\;\; c^2 / 2k_b\nu^2 \;\;=\;\; B\;\; \lambda^2 / 2k_b$$

Brightness temperature (a temperature that will result in a given brightness if inserted into the Rayleigh-Jeans law)

$$T_A\,(\theta_0,\varphi_0\,) \;=\; \frac{\int\!\!\int \; T_b(\theta,\varphi)\;\; P_n(\theta\!-\!\theta_0\,,\; \varphi\!-\!\varphi_0)\; \sin\theta\;\, d\theta\;\, d\varphi}{\int\!\!\int \;\; P_n(\theta\,,\; \varphi)\; d\Omega}$$

——> convolution of the brightness temperature distribution with the beam pattern results in an antenna temperature measurement for a certain direction (θ_0,φ_0) … ("full circle" with regard to the beginning of today's lecture ...)

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Scripts at : http://www.mpia.de/homes/beuther/lecture_ws1213.html

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