Single-dish Radioastronomy in the mm/submm domain

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(based on IMISS lectures)

Outline

- Introduction
- Antenna
- Source flux and antenna temperature
- Heterodyne receiver
- Spectrometer
- Calibration
- Observations

Main dingle-dish antenna

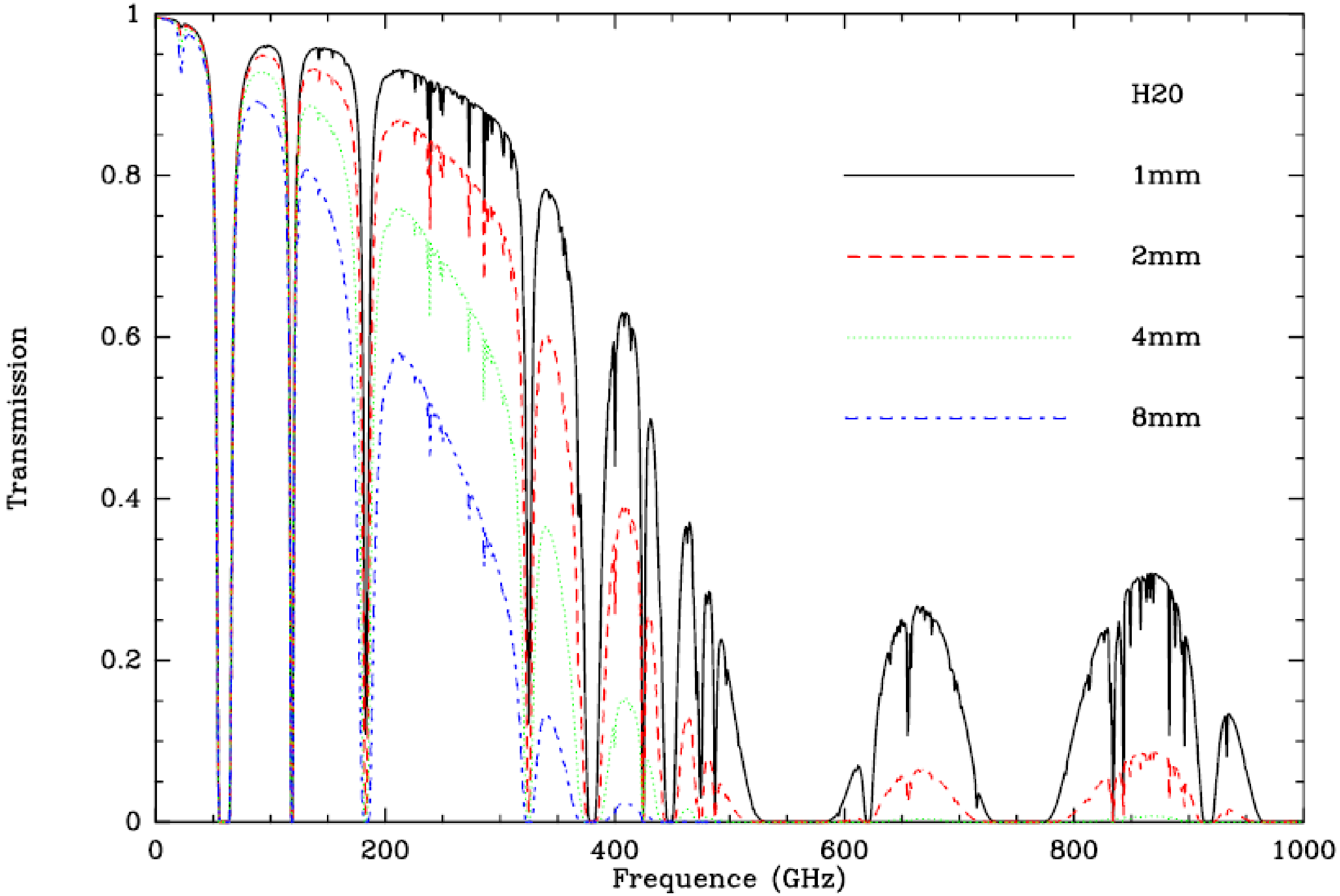
Institute	Diameter (m)	Frequency (GHz)	Wavelength (mm)	HPBW ($''$)	Latitude
Max-Planck	100	$0.09 - 1.15$	$3 - 300$	$11 - 680$	$+47^\circ$
IRAM	30	$80 - 280$	$1 - 3$	$9 - 30$	$+37^\circ$
JCMT	15	$210 - 710$	$0.2 - 2$	$8 - 20$	$+20^\circ$
APEX	12	$230 - 1200$	$0.3 - 1.3$	$6 - 30$	-22°
CSO	10.4	$230 - 810$	$0.4 - 1.3$	$10 - 30$	$+20^\circ$

IRAM-30m

JCMT-15m

APEX-12m

Atmospheric window in the mm/submm domain

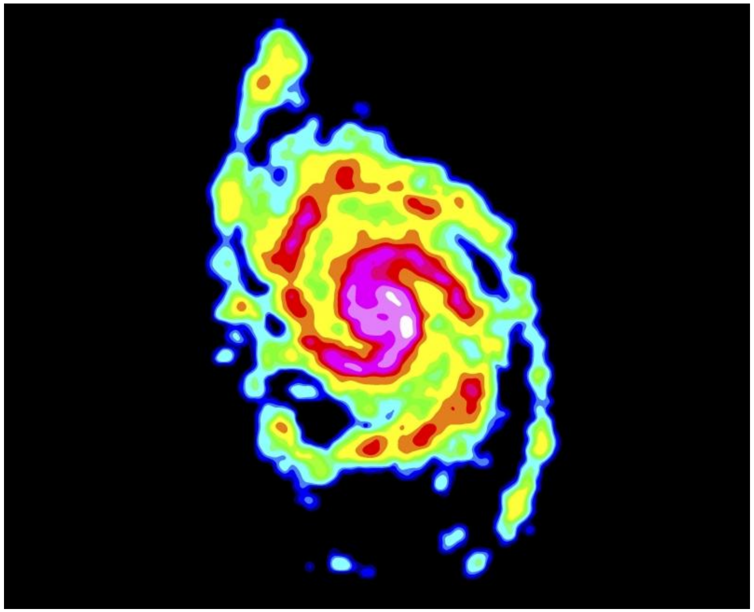


Atmospheric absorption mainly due to vapor of H_2O and O_2

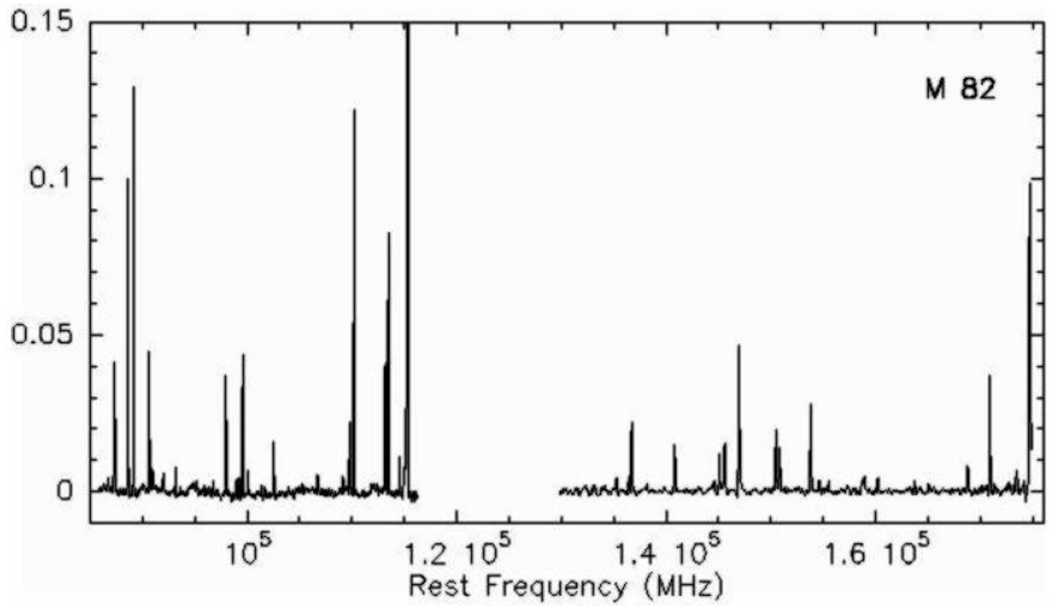
-H_2O at 22,183, 325, 557, 752,916, 987 GHz

- O_2 at 60, 118 GHz

A little bit of science



Whirlpool galaxy (M51)
CO integrated map

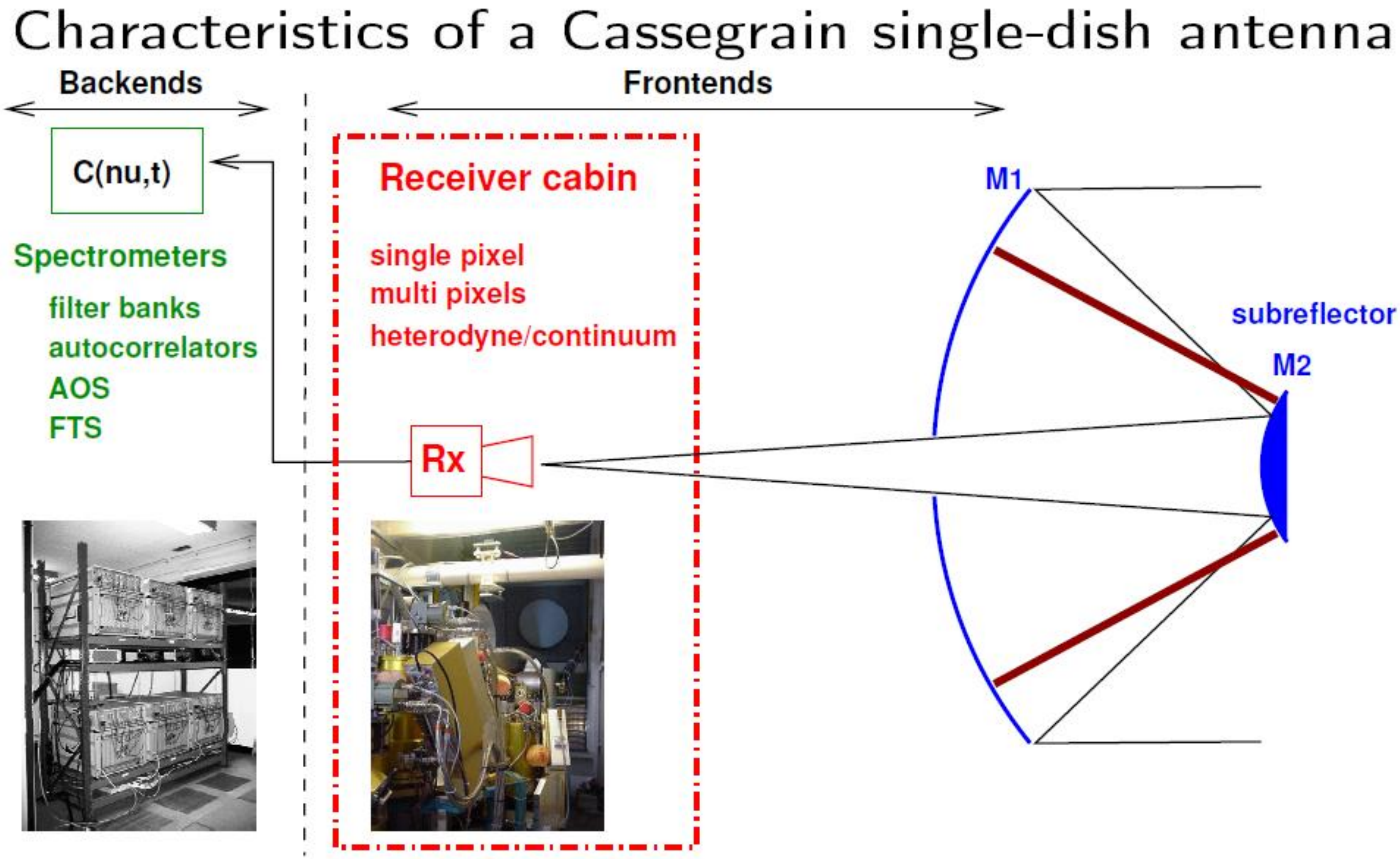


M82 – spectral survey

Antenna

IRAM-30m
-Granada/Spain (Pico Veleta)
-altitude of 3000 m

Overview


Characteristics of a Cassegrain single-dish antenna
Backends
Frontends
C(nu,t)
Spectrometers
filter banks
autocorrelators
AOS
FTS
Receiver cabin
single pixel
multi pixels
heterodyne/continuum
Rx
M1
subreflector
M2

Terminology

Antenna (e.g. IRAM-30m) Beam (PSF) = 1.2*λ/D = 8-30" - FoV

Frontend

Receiver (Rx)

-Bandwidth (BW)

$\Delta\nu$ =0.5-8 GHz

-Sky frequency (ν_s)

ν_s=80-1200 GHz

(i.e. λ_s =3-0.3mm)

-Polarization

Bolometer

$\Delta\nu = \delta\nu$ =50 GHz

e.g. NIKA2 (196 pixels, Fov ~2')

Backend

Spectrometers

-Autocorrelator

-Fourier transf. (FTS)

-Filter Bank (FB)

-Acousto Optics (AOS)

-Spectral resolution ($\delta\nu$)

-$\delta\nu$ (min) = 10-100 KHz

-Power spectral resolution (R)

-R =$\nu_s / \delta\nu > 10^6 - 10^7$

dV > 10 m/s

Antenna

Why Cassegrain configuration ?

We want a large F/D

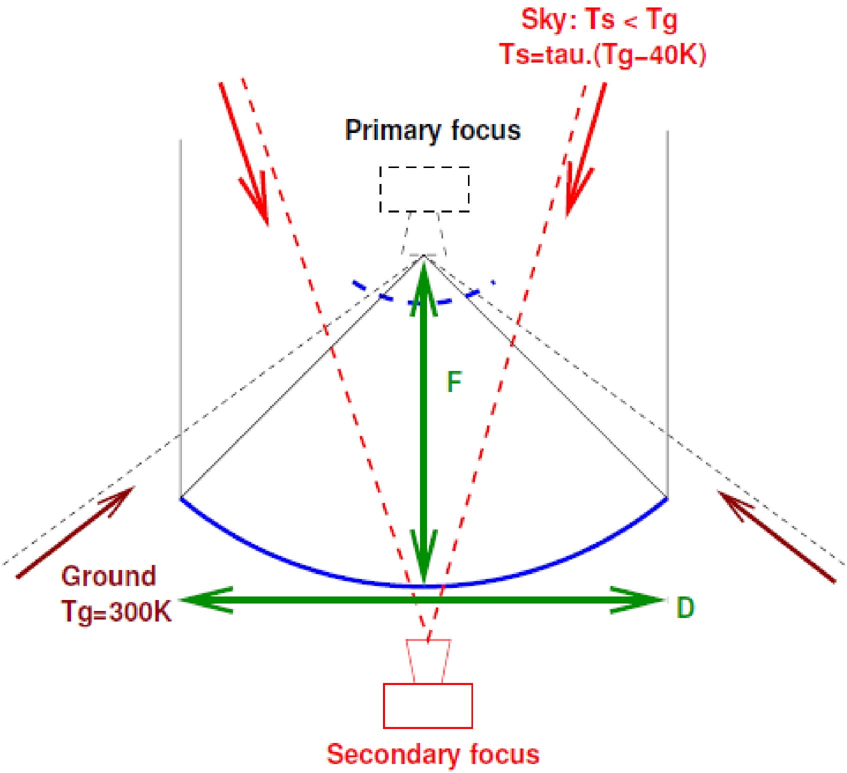
- increase effective area (or on-axis gain)
- use secondary focus: decrease spillover
- Rx alignement more easily acheived; focal plane arrays
- *but increase mechanical load*

$\Rightarrow$ Cassegrain configuration

$+$ Effective ratio $F_e/D = m(F/D)$

$-$ obstruction by subreflector ($\varnothing = 2$ m at 30-m) $\Rightarrow$ wider main-beam

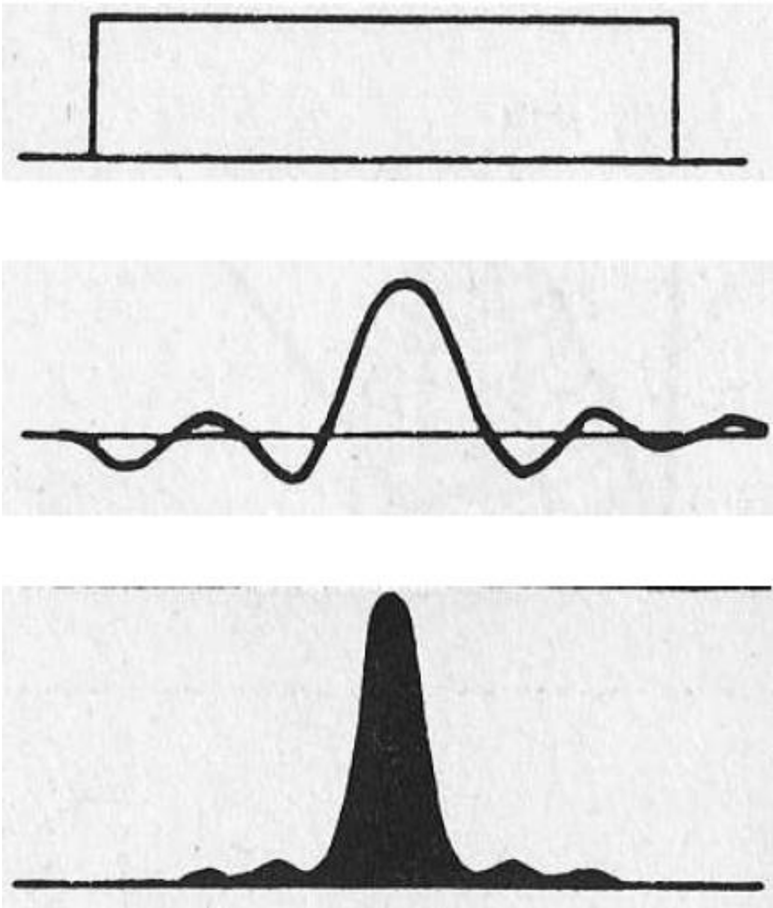
- 30m antenna:
  $F/D = 0.35$, $m = 27.8$, $F_e/D \approx 10$

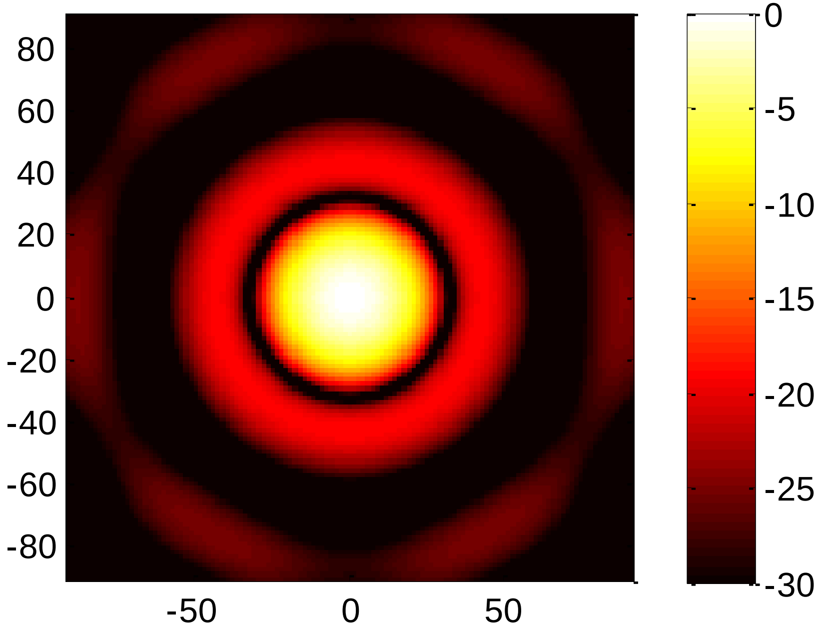


Ideal Beam Pattern

Diffraction theory,
Huygens-Fresnel, Franhoffer approx.
$E(\theta,\varphi)$ = Fourier Transform [$E_{ant}(x,y)$]

Sharp cut of the antenna domain
-oscillation (sidelobe)
➔ Taper (apodisation)



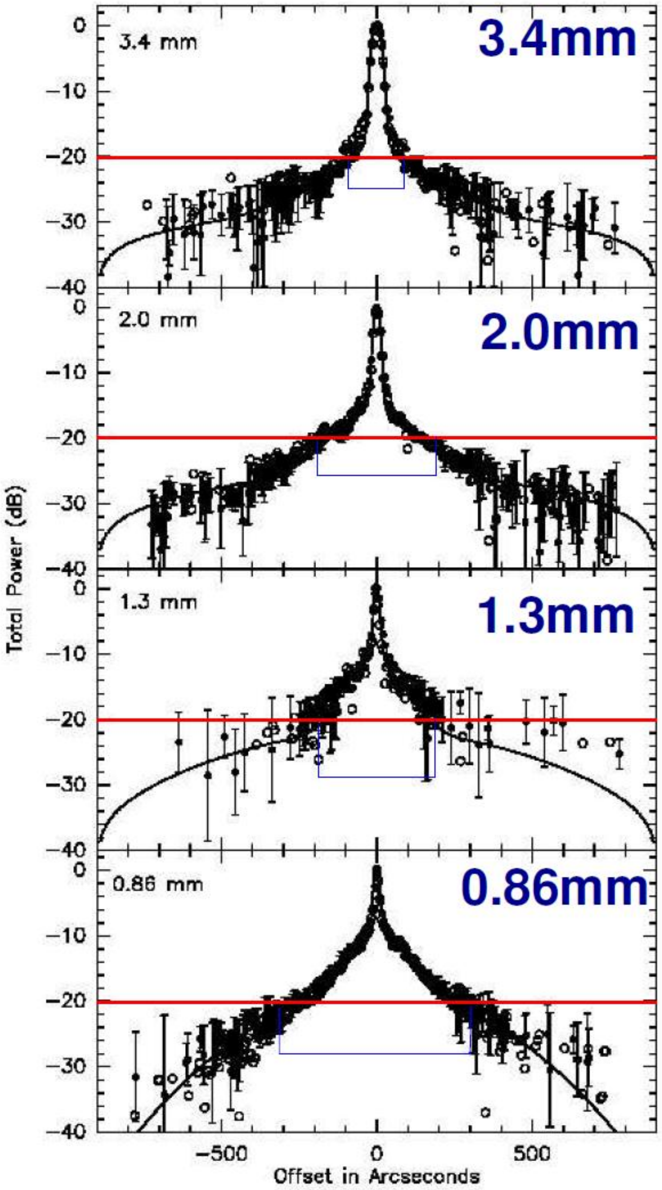


Real Beam Pattern

-Secondary beams (finite surface antenna)
-Error beams (surface imperfection)

real beam : main beam + error beam

➔ Important for extended sources



Antenna Diagram

The antenna pattern is the telescope response to a point source, as a function of angle, normalized to unity on axis:

$$P_n(\theta,\varphi) = P(\theta,\varphi) / P\mathrm{max}$$

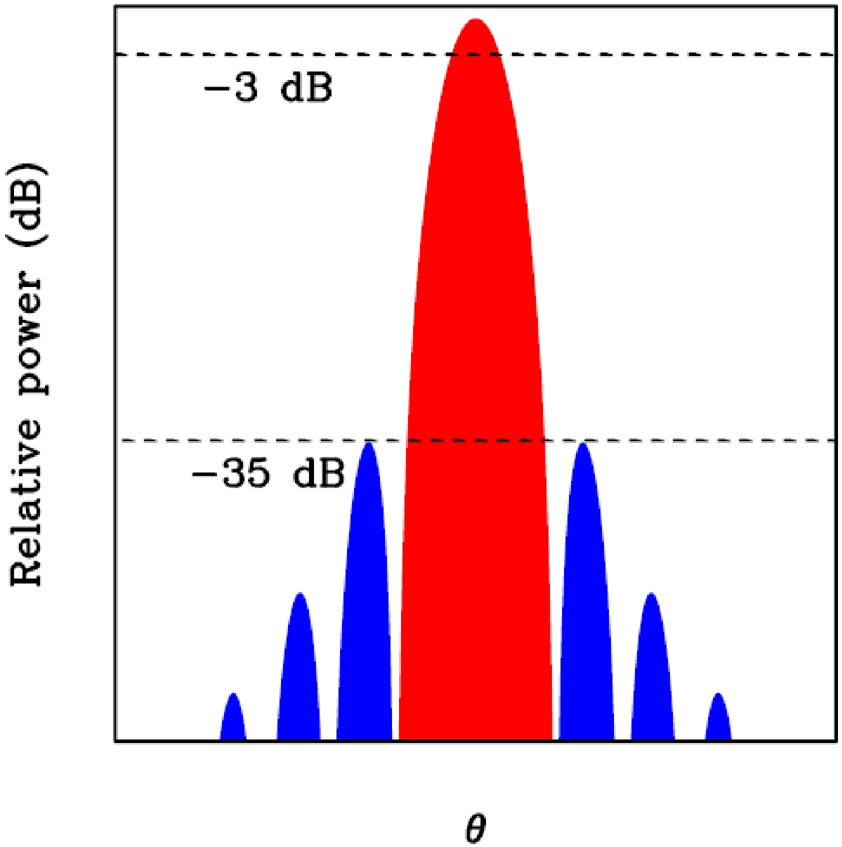
The beam solid angle Ω_A is defined by

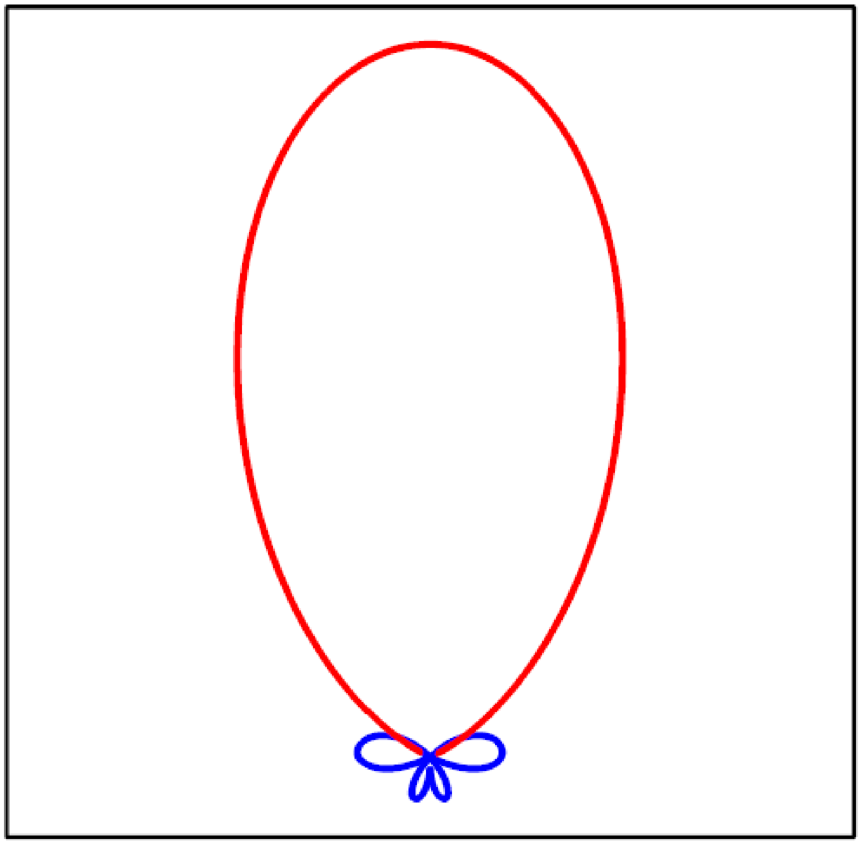
$$\Omega_A = \iint_{4\pi} P_n(\theta,\varphi)\, d\,\Omega$$

The spatial resolution of a telescope is characterized by the Half Power Beam Width (HPBW) of the main lobe (i.e. PSF)

$$\mathrm{HPBW} \sim 1.2 * \lambda / D$$

Antenna diagram





The main beam (in red) may often be simplified by a gaussian shape while the secondary beams (in blue) are more complex.

Source flux density (I)

The flux density $S_{\nu\,,tot}$ that is the power radiated per unit area and per unit frequency (S_ν in Jansky : 1 Jy = 10^{-26} $W.m^{-2}.Hz^{-1}$) from a radio source at a given frequency, is given by

$$S_{\nu\,,tot} = \int_{\Omega s} B(\nu)\ \psi(\theta,\varphi)\ d\ \Omega$$

$B(\nu)$ is the planck's law

$\psi(\theta,\varphi)$ describes the normalized spatial brightness distribution of the source: $\psi(0,0) = 1$ and $\psi(\theta,\varphi) = 0$ outside the source.

Ω_S is the source solid angle:

$$\Omega_{S\,=} = \int_{4\pi} \psi(\theta,\varphi)\ d\ \Omega$$

Source flux density (II)

$$S_{\nu\,,tot} = 2k\,\nu^2/c^2 \int_{\Omega s} J_\nu(Tb)\;\psi(\theta,\varphi)\;d\,\Omega$$

Tb is the Planck brightness temperature of the source.

$J_\nu(Tb)$ is the Rayleigh-Jeans brightness temperature at the frequency ν :

$$J_\nu(Tb) \equiv T_{RJ} = h\nu/k\;[\exp(h\,\nu/kTb\,)-1]^{-1}$$

where k is the Boltzman constant.

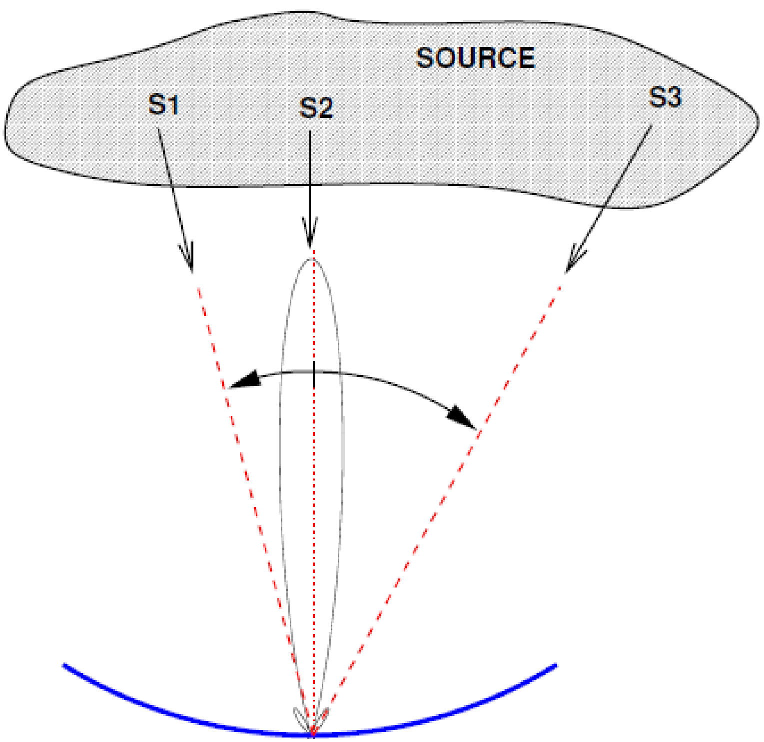
Note, at cm radioastronomy the Rayleigh-Jeans approximation ($h\,\nu/kTb << 1$) being often valid, gives $S_{\nu\,,tot} = 2kT/\lambda^2\,.\Omega_S$

Antenna Temperature

The measured antenna temperature [K] is given by the convolution integral of the antenna diagram and source brightness distribution:

$$Ta^*(\theta,\varphi) = 1/(\eta_l \Omega_A) \int_{\Omega s} P(\theta,\varphi)\, J_\nu(\nu)\, \psi(\theta,\varphi)\, d\,\Omega$$

Where η_l is the ratio of power detected from the forward hemisphere to the total power detected *the so-called forward efficiency (Feff)*



Feff ~0.9

Aperture Efficiency and point source sensitivity

The aperture efficiency can be determined via the observed peak antenna temperature Ta^* of a point like source when its total flux density $S_{\nu\,,beam}$ is known.

$$\eta_a = A_{eff}/A_{geom} = 2k/\,A_{geom}\,Ta^*\,/\,S_{\nu\,,beam}$$

$$\Rightarrow \eta_a = 2k/\,A_{geom} * 1/\,\chi_{pss}$$

thereby also defining the point source sensitivity χ_{pss} in Jansky per Kelvin which is often used instead of η_a

$$\chi_{pss} = S_{\nu\,,beam}\,/\,Ta^* \quad \text{[in Jy/k]}$$

Main Beam Efficiency (I)

The main beam efficiency is defined as the percentage of power entering through the main beam between the first nulls.

$$\eta_{mb} = \Omega_{mb} / \Omega_a$$

The main beam efficiency (Beff) is linked to ηa.
For a gaussian beam : Beff ~ 1.2 ηa

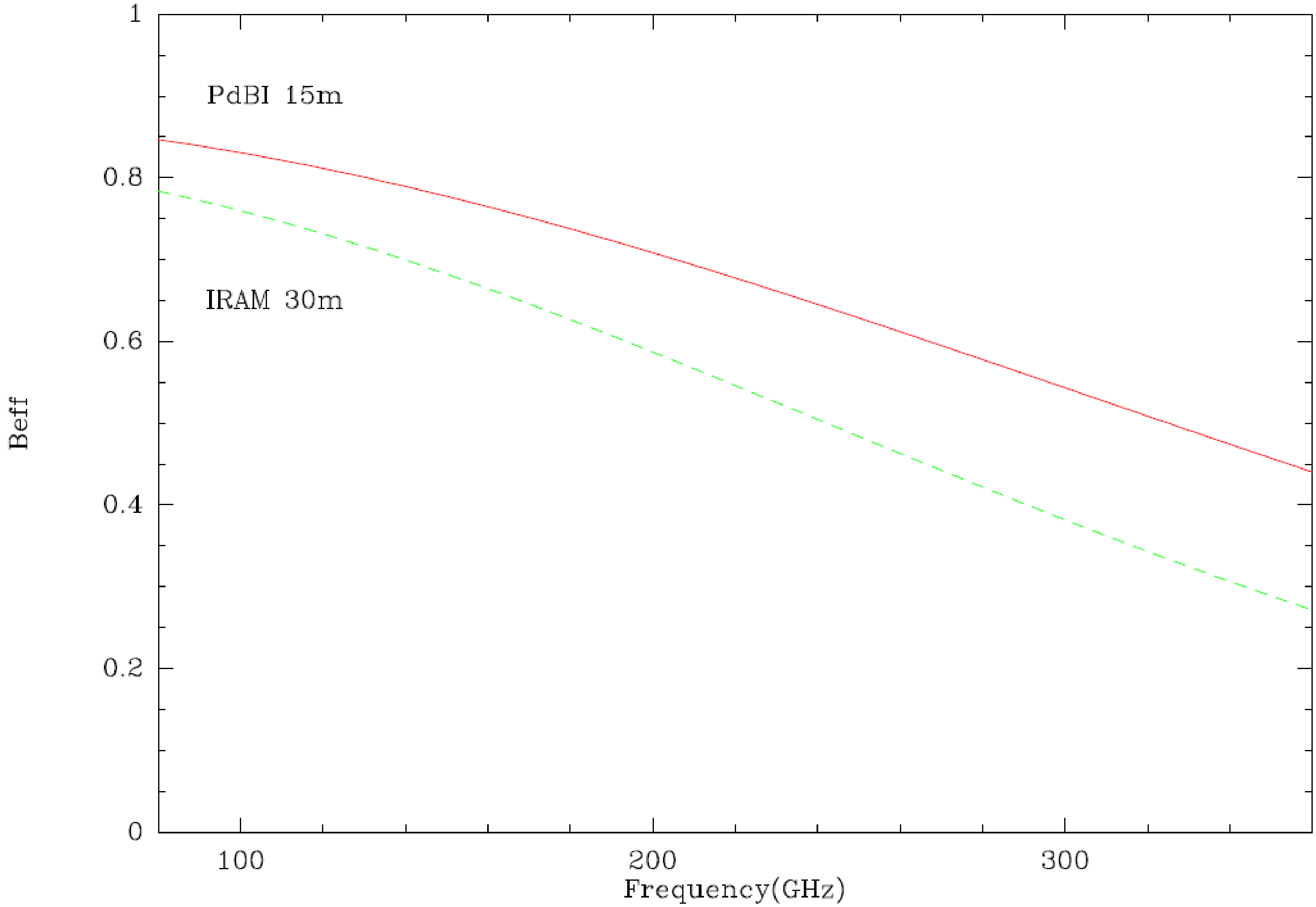
$$\mathrm{Beff} = \mathrm{Beff0} * \exp^{(-(4\pi\sigma/\lambda)^2)}$$

Where σ is the surface rms accuracy
(e.g. σ = 50 µm for the IRAM-30m)

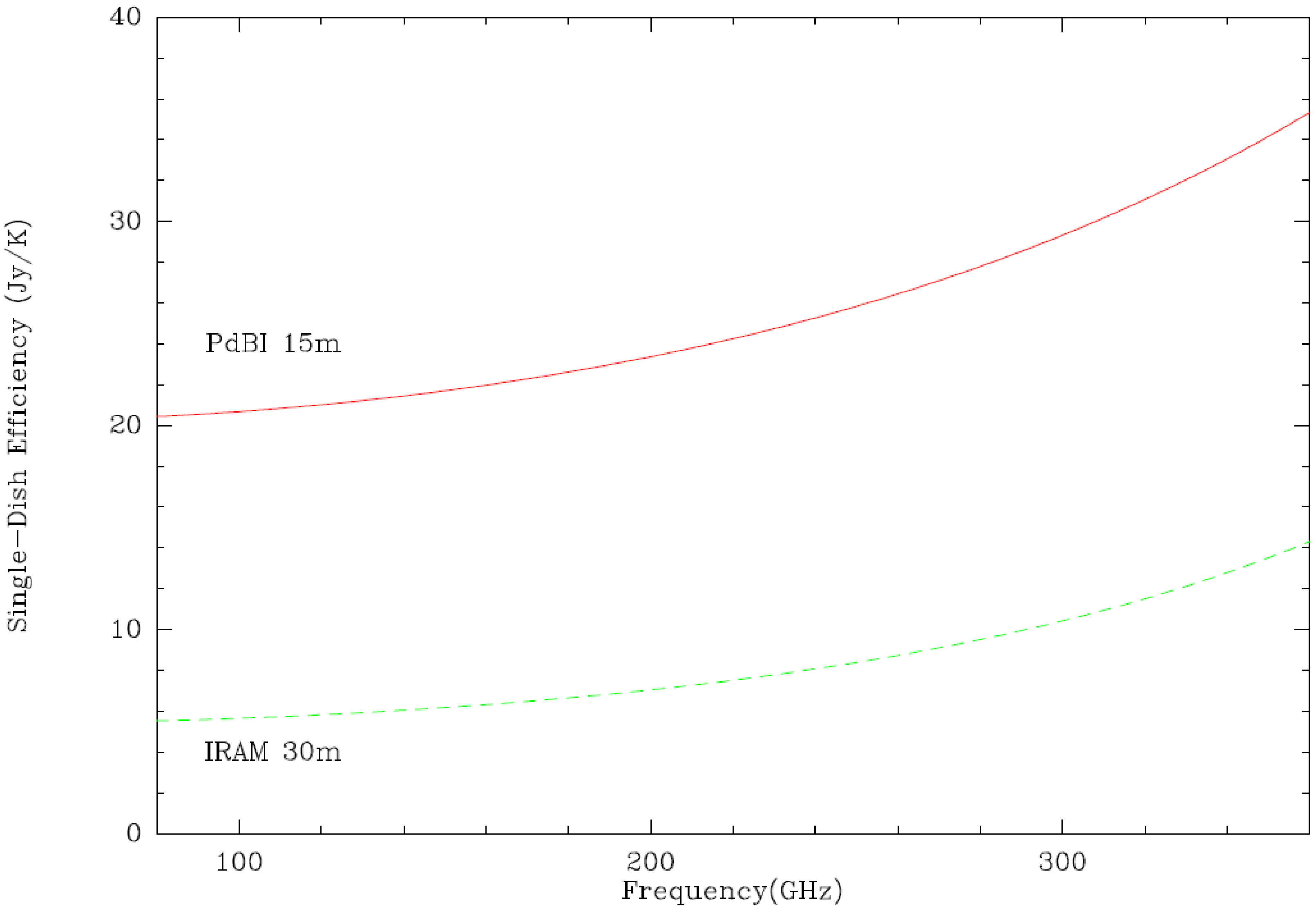
Main beam temperature

$$\mathrm{Tmb} = \mathrm{Feff/Beff} \, .\mathrm{Ta}^*$$

Main Beam Efficiency (Beff)



Point source sensitivity (Jy/K)



Correction for non point-like source

the correction factor K

$$Ta^* = S_{\nu\,,tot}\,.A_{eff}/(2k.Feff).K$$

With

$$K = [1\text{-}\exp^{(-x^2)}\,]/x^2 \;<1$$

For a gaussian beam , $x = (\ln 2)^{0.5}.\theta_s/\theta_b$
θ_s is the source angular diameter
θ_b is the beam size

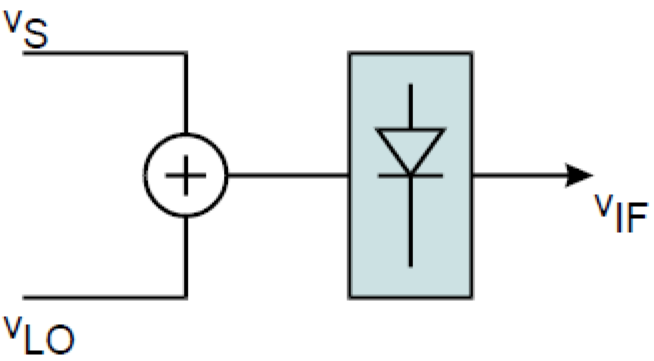
Frontend

Heterodyne Receiver

<u>Heterodyne</u> : refer to a receiver where the input frequency ν_s is shifted to a lower frequency ν_{if} (called intermediate frequency).

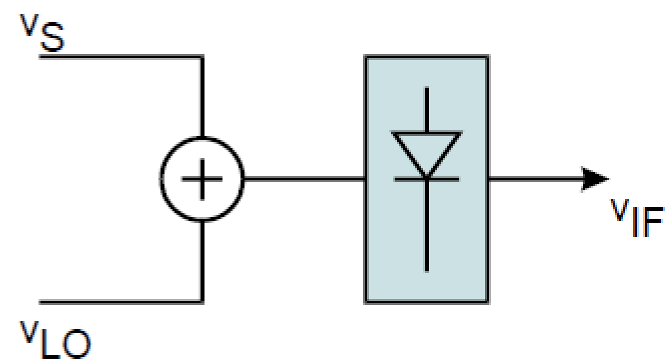
This is done by adding a local oscillator frequency ν_{lo} and passing the sum in a non-linear device called mixer.
ν_{if} can be more easily amplified.

$\nu_{lo} \sim \nu_s \sim$ 80-1200 GHz
$\nu_{if} \sim$ 4-12 GHz

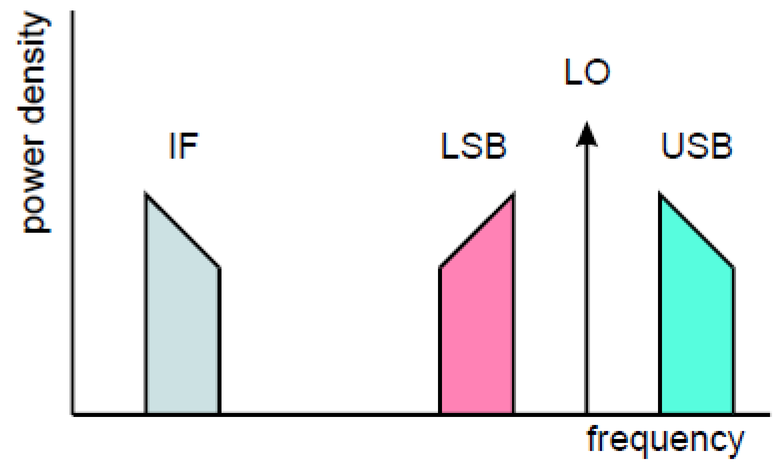


Heterodyne Receiver

$v_{lo} = V_{lo} \, . \cos(\omega_{lo} t)$
$v_s = V_s \, . \cos(\omega_s t + \varphi_s)$
$v_{if} = A.(v_{lo} + v_s)^2$



$v_{if} = A.V_{lo} \, .V_s \cos[(\omega_s - \omega_{lo})t + \varphi_s] + \ldots$
$v_{if} = A.V_{lo} \, .V_s \cos[(\omega_{lo} - \omega_s)t + \varphi_s] + \ldots$



Upper side Band (USB)
USB : $\omega_s > \omega_{lo}$

Lower side Band (LSB)
LSB : $\omega_s < \omega_{lo}$

gs and gi are the receiver gain in the signal and image band (i.e. USB or LSB) , with gs+gi=1. g is the image to gain ratio g= gs/gi

SIS Junction

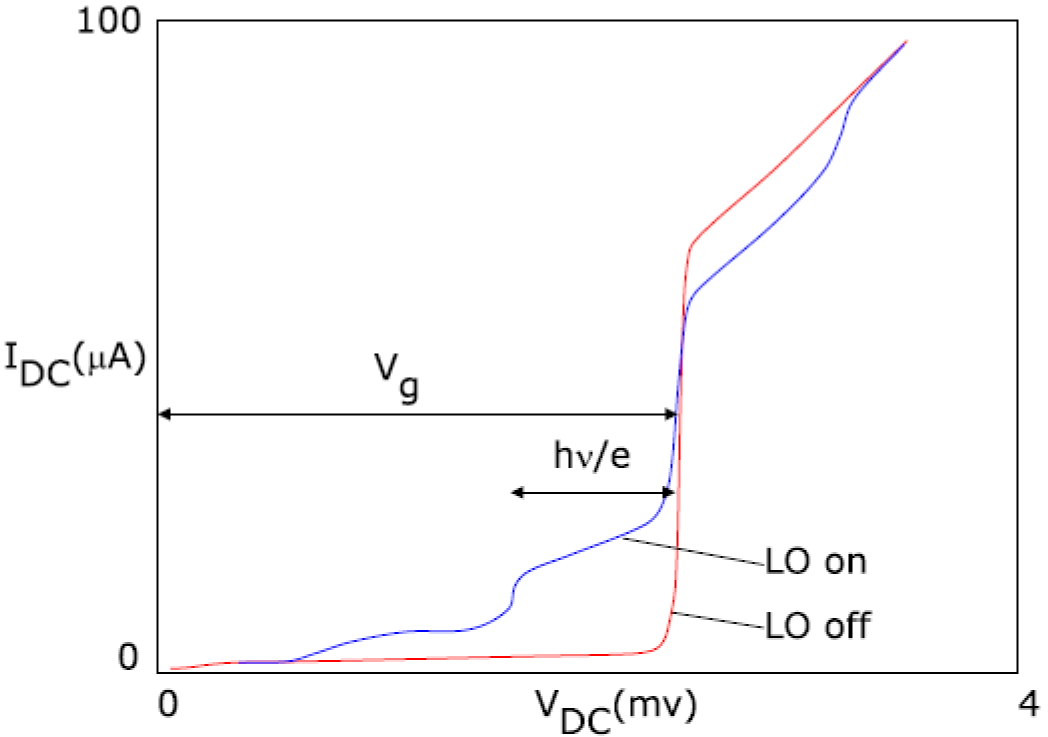
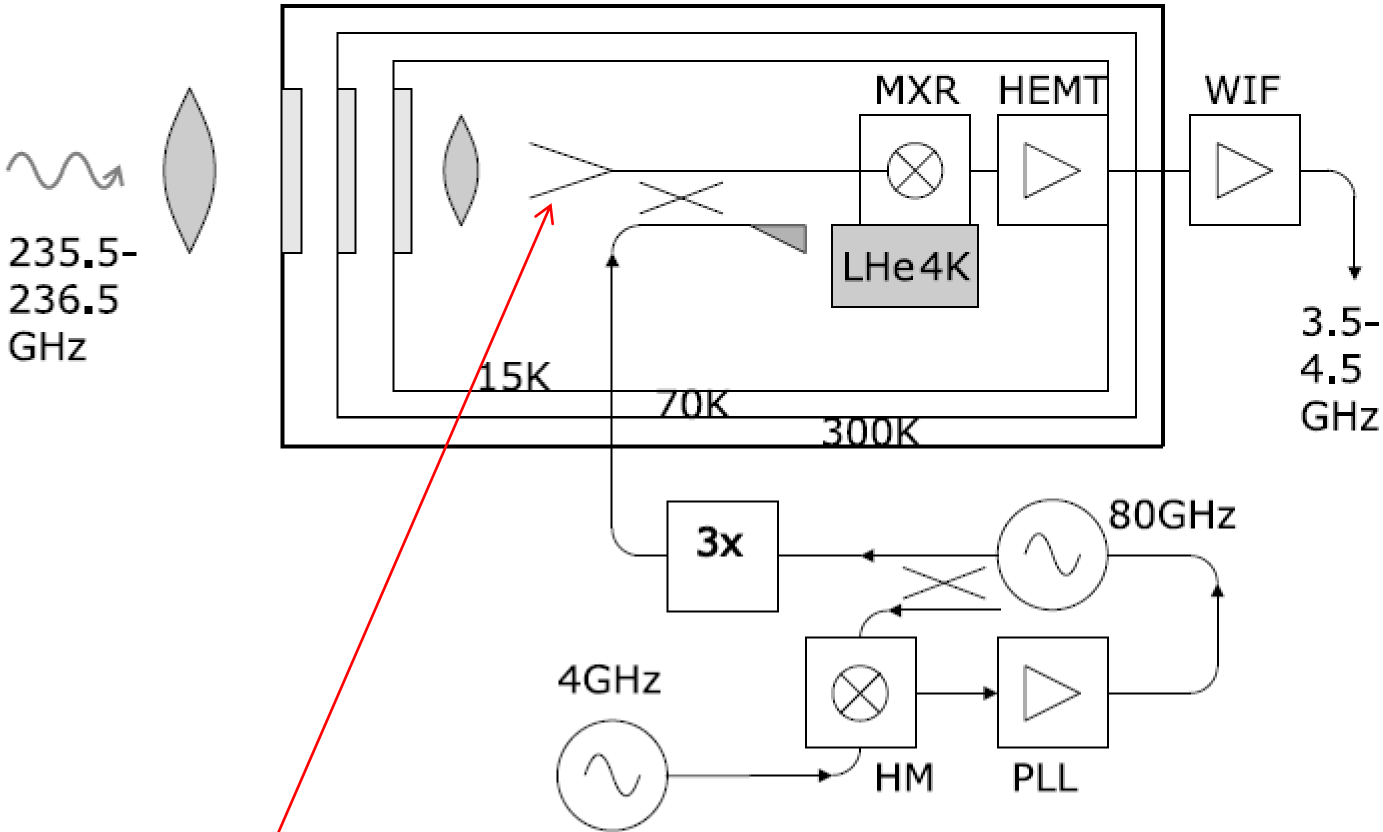


Figure 5.5: Current-voltage characteristics of an SIS junction operating in a mixer. The two curves were measured without and with LO power applied (frequency 230GHz); they have been slightly idealized (for pedagogical reasons, of course).

The SIS junction is a supraconductrice-isolant-supraconductrice diode made with (Nb-N) in the mm/submm domain.

It is a Non-linear diode, which works at a temperature of 4K,
This junction is the detector present in the mixer device.

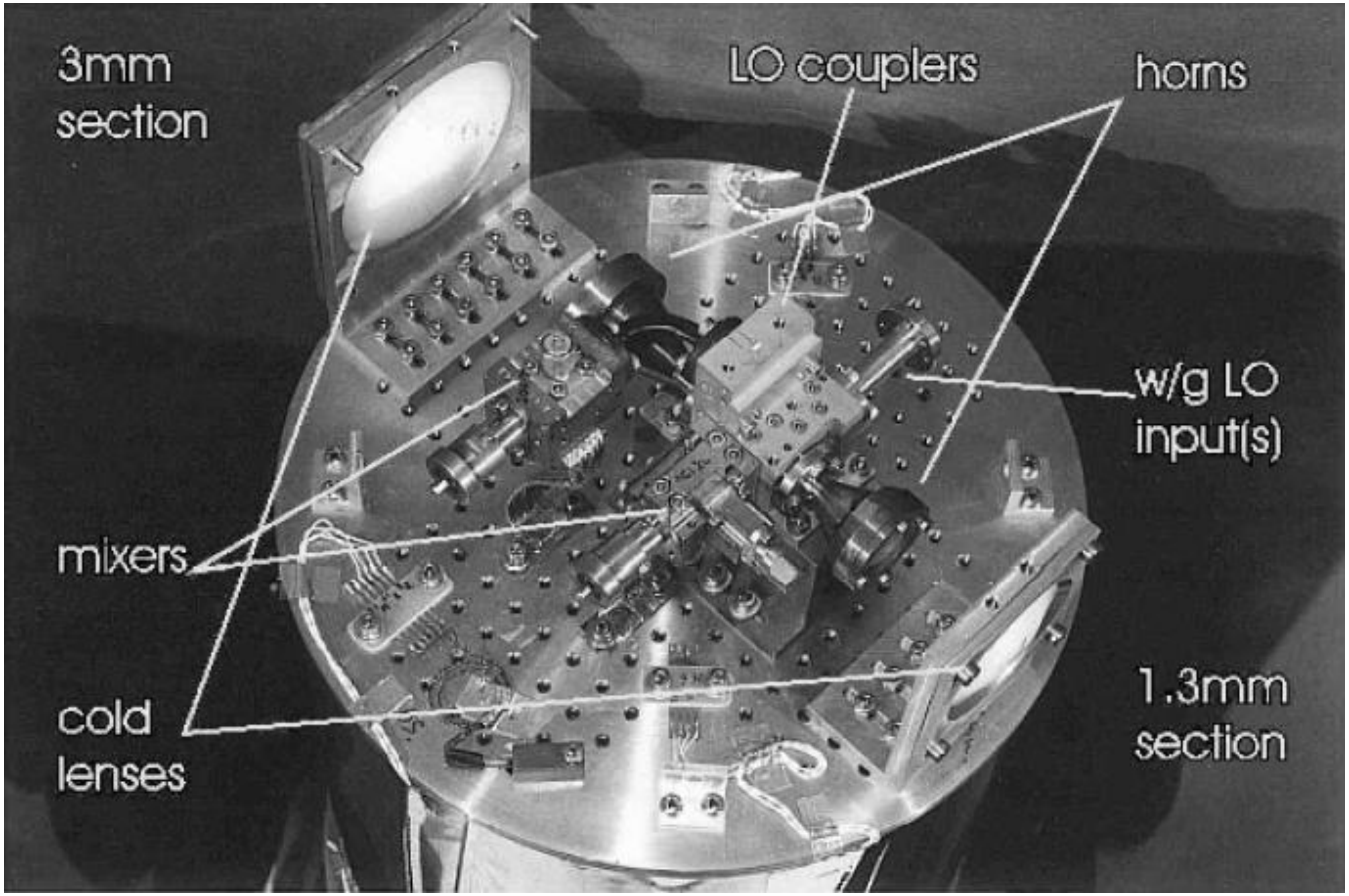
Heterodyne Receiver



-Diagram of a heterodyne receiver within a cryostat – **single pixel**

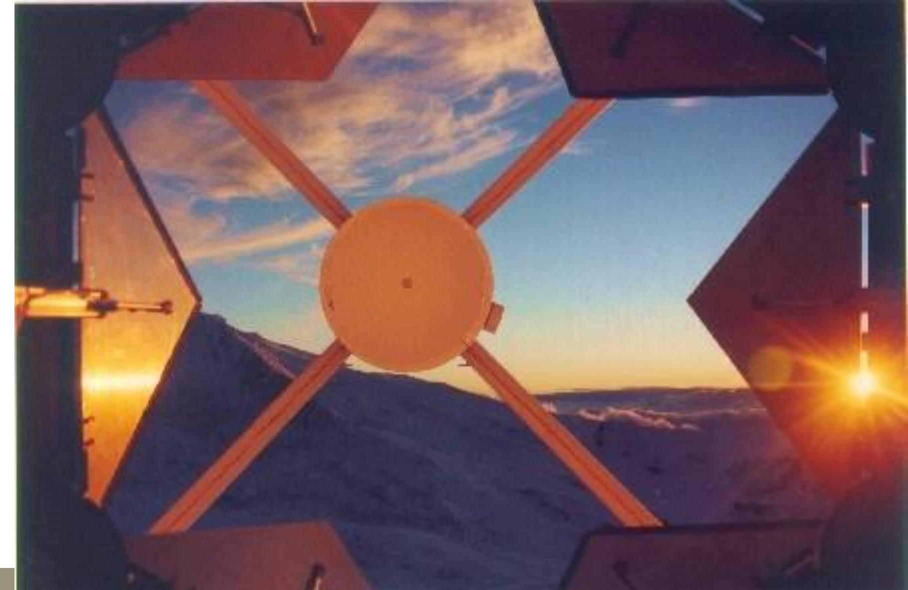
-Entrance **horn** allow to measure **only a single polarization** (i.e. H or V, which means 50% of the signal)

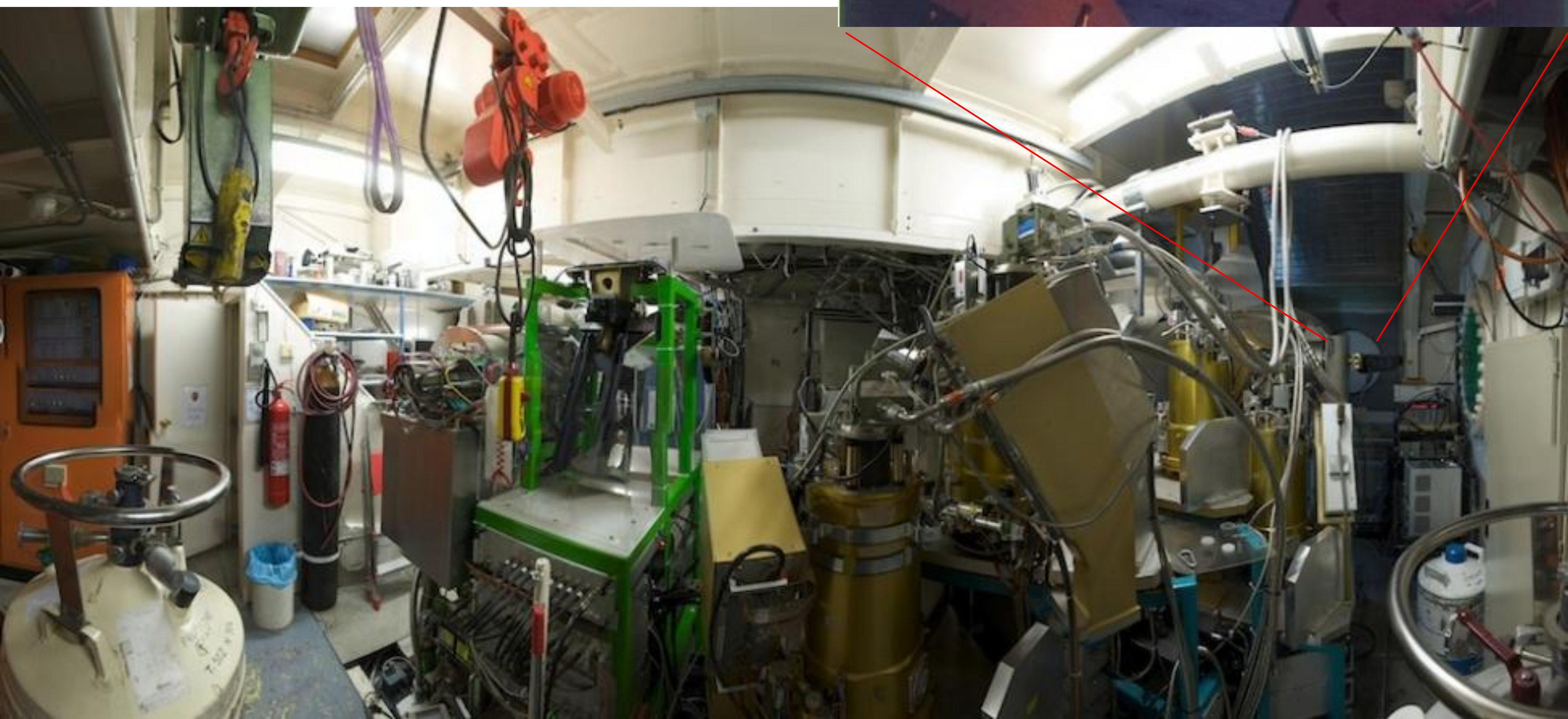
Heterodyne Receiver



The noise (i.e. sensitivity) of an heterodyne receiver is characterized by its receiver temperature (Trec ~50-80 K in the mm domain).

Receiver Cabin





Backend

Spectrometers

-Autocorrelator
-Fourier transform spectrometer (FTS)
-Filter Bank (FB)
-Acousto Optics (AOS)

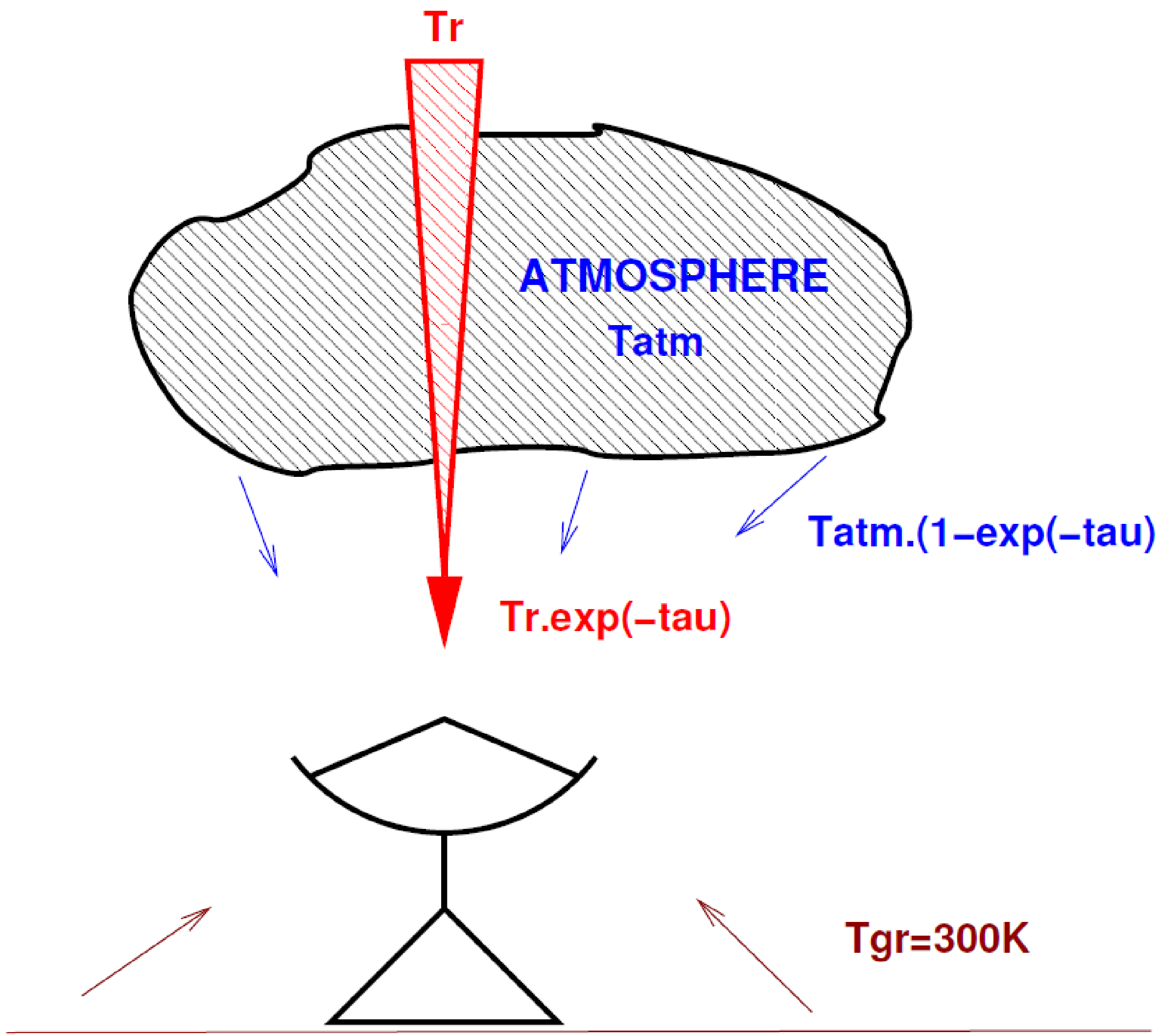
-Spectral resolution ($\delta\nu$)
-$\delta\nu$ = 10-1000 KHz

-Power spectral resolution (R)
-$R = \nu 0 / \delta\nu > 10^6 - 10^7$

-Digital quantification loss : $\eta c \sim 0.9$

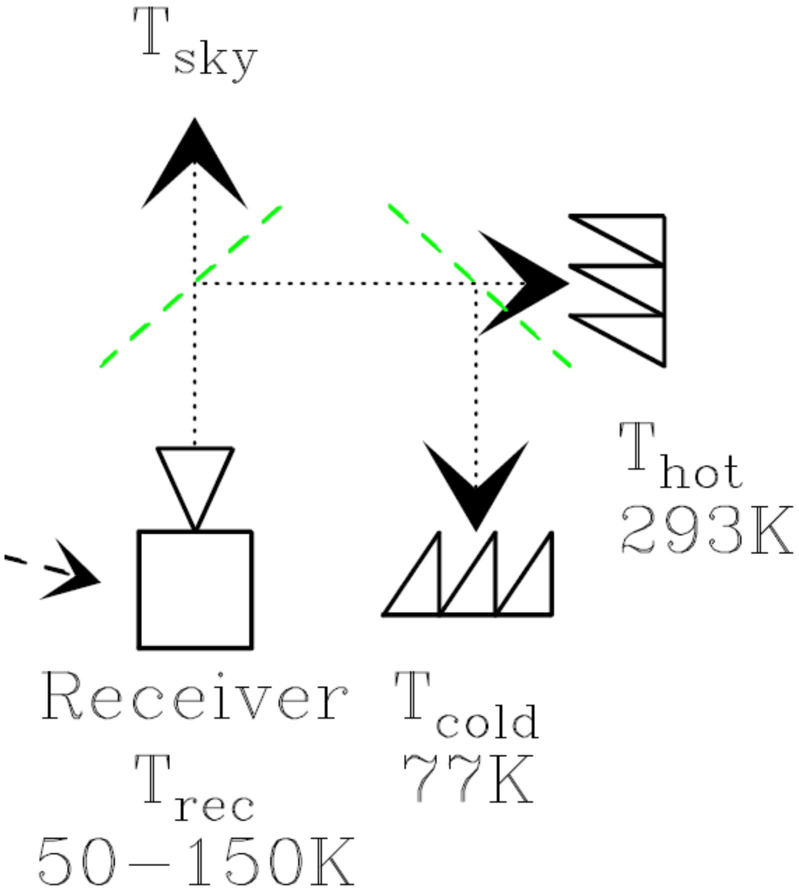
Calibration

Atmosphere



$$T = \alpha \left\{ T_R e^{-\tau_\nu} + (1 - e^{-\tau_\nu}) T_{\rm atm} \right\} + (1 - \alpha) T_{\rm gr}$$

Calibration scheme



Scheme of a Dual-load calibration device

BASIC EQUATIONS

The receiver power output P_{X} are proportional to the emission J_{X} from a load or the sky :

$$P_{\mathrm{hot}} = K(T_{\mathrm{rec}} + J_{\mathrm{hot}})$$

$$P_{\mathrm{cold}} = K(T_{\mathrm{rec}} + J_{\mathrm{cold}})$$

$$P_{\mathrm{sky}} = K(T_{\mathrm{rec}} + J_{\mathrm{sky}})$$

T_{rec} is the receiver temperature, and K is the detector gain.

Single-Dish source Measurement :

$$C_{ON-OFF} \simeq K(g_s \eta \exp^{-\tau} T_a^*)$$

Interferometer cross–correlation :

$$C_{source} = K(g_s \eta \exp^{-\tau} T_a^*)$$

T_a^* is the source antenna temperature corrected from the atmospheric absorption and η is the forward efficiency.

Dual-Load Calibration

In the dual-load calibration system, a cold and an ambient temperature loads are used in general.

$$T_a^* = \frac{e^\tau}{g_s\eta}(J_{\rm hot} - J_{\rm cold})\frac{C_{\rm source}}{P_{\rm hot} - P_{\rm cold}} = T_{\rm cal}\frac{C_{\rm source}}{P_{\rm hot} - P_{\rm cold}} \tag{9}$$

where the calibration temperature is now

$$T_{\rm cal} = \frac{(1+g)e^\tau}{\eta}(J_{\rm hot} - J_{\rm cold}) \tag{10}$$

Accurate calibration requires accurate knowledge of τ, η, g and of the effective load temperatures.

Atmospheric opacity

The atmospheric emission, $J_{\rm atm}$, can be computed as :

$$J_{\rm atm} = \frac{J_{\rm sky} - (1-\eta) J_{\rm spill}}{\eta} = J_{\rm m}(1 - \exp^{-\tau})$$

from the ATM program

input : $J_{\rm atm}$

output : $J^s_{\rm atm}, J^i_{\rm atm}, \tau_s, \tau_i, H_2O,$ **and also ,** $J^s_{\rm m}, J^i_{\rm m}$

System temperature (Tsys)

The global system noise (receiver and atmosphere) is know as the system temperature ($T_{\rm sys}$) and can be computed as :

$$T_{\rm sys} = \frac{(1+g)}{\eta \exp^{-\tau}}[\eta J_{\rm atm} + (1-\eta) J_{\rm spill} + T_{rec}]$$

under normal weather conditions (pwv ~ 2-4 mm at 3000m)
Tsys ~ 100-300 K in the mm domain

Observations

Observation sequence

-**Receiver** tuning at the frequency ν_s
-**Correlator** setup of all units (i.e. $\delta\nu$)

-**Calibration** : Trec, Tsys, atmospheric opacity (τ)
(e.g. Chopper wheel method on a dual-load calibration system)

-**Pointing** check : on a nearby quasar or a planet with strong signal.
[move the antenna in Δ(Azimuth), Δ(Elevation) i.e. X,Y plane]

-**Focus** check : also on a quasar or a planet
[move the sub-reflector in the Z axis]

-**Observation** on Source (i.e. **ON-OFF** see next slide)

Observing method

ON-OFF to eliminate the atmospheric and background contribution

-PSW : **Position switching** (antenna movement : t~ 30 s)

-WSW : **Wobbler switching** (secondary mirror movement : t~ 2 s)

-FSW : **Frequency switching** (change ν_{lo} by ~ 10 MHz : t ~ 1s)

double the integration time ON source. Adapted for narrow lines.

Map with a single pixel receiver :

-perform several measurement points (nx,ny)

Map with a multi-pixel receiver (e.g. 7) :

Same as before , but faster for large map

-On-the-Fly mapping (OTF) :

continuous antenna movement and integration.

Single-Dish Sensitivity (I)

In antenna temperature

$$\Delta Ta^* \text{ [K]} = Tsys / [\eta c(A.\delta\nu.t_{tot})^{0.5}]$$

Where t_{tot} is the total integration time (ON+OFF),

In flux

$$\Delta S \text{ [Jy]} = \chi_{pss}\,.\,\Delta Ta^* = \chi_{pss}\,.\,Tsys / [\eta c(A.\delta\nu.t_{tot})^{0.5}]$$

The factor A depends on the observing method :

A(PSW) = 0.25 for PSW and WSW

A(FSW) = 0.50 for FSW

Including overhead (calibration, pointing, focus, …)

<u>for 50% observing efficiency</u> A(PSW) = 0.125 and A(FSW) = 0.25

Single-Dish Sensitivity (II)

Line	**Continuum**
WSW observation of CO(2-1) ν_s = 230.538 GHz $\delta\nu$ = 1 MHz, Tsys ~200 K, ηc=0.90, χ_{pss} = *8 Jy/K* Ttot = 1 hour , Observing efficiency = 50% ➔ A=0.125	WSW observation ν_s = 230.538 GHz $\delta\nu$ = 8 GHz, Tsys ~200 K, ηc=0.90, χ_{pss} = *8 Jy/K* Ttot = 1 hour , Observing efficiency = 50% ➔ A=0.125
ΔTa* = 10 mK or ΔS = 84 mJy	ΔTa* = 0.1 mK or ΔS = 0.9 mJy
Tb = 20 K - θ_s = 1” ➔S(230GHz) = 450 mJy Tmb = 85 mK - Ta* = 56 mK ➔ SNR ~5	Tb = 50 K - θ_s = 1” ➔S(230GHz) = 1.3 Jy Tmb = 0.25 K – Ta* = 0.17 K ➔ SNR ~ 150

Summary for Proposal

Before writing a proposal , one need to check :

-The integration time needed to perform its science.
 (max few 10-50 of hours at the IRAM-30m)
Use the time estimator : http://www.iram.es/nte/

-Spatial resolution needed (8-30” IRAM-30m)

-Mapping FOV (reasonable max ~ 2-10’ at IRAM-30m)

- Optimize the tuning and spectral setup

-RA, DEC of the source (source elevation > 20°)