Introduction to Radioastronomy:

Observing techniques

Observatoire astronomique de Strasbourg

J.Köppen joachim.koppen@astro.unistra.fr

http://astro.u-strasbg.fr/~koppen/JKHome.html

Observing …

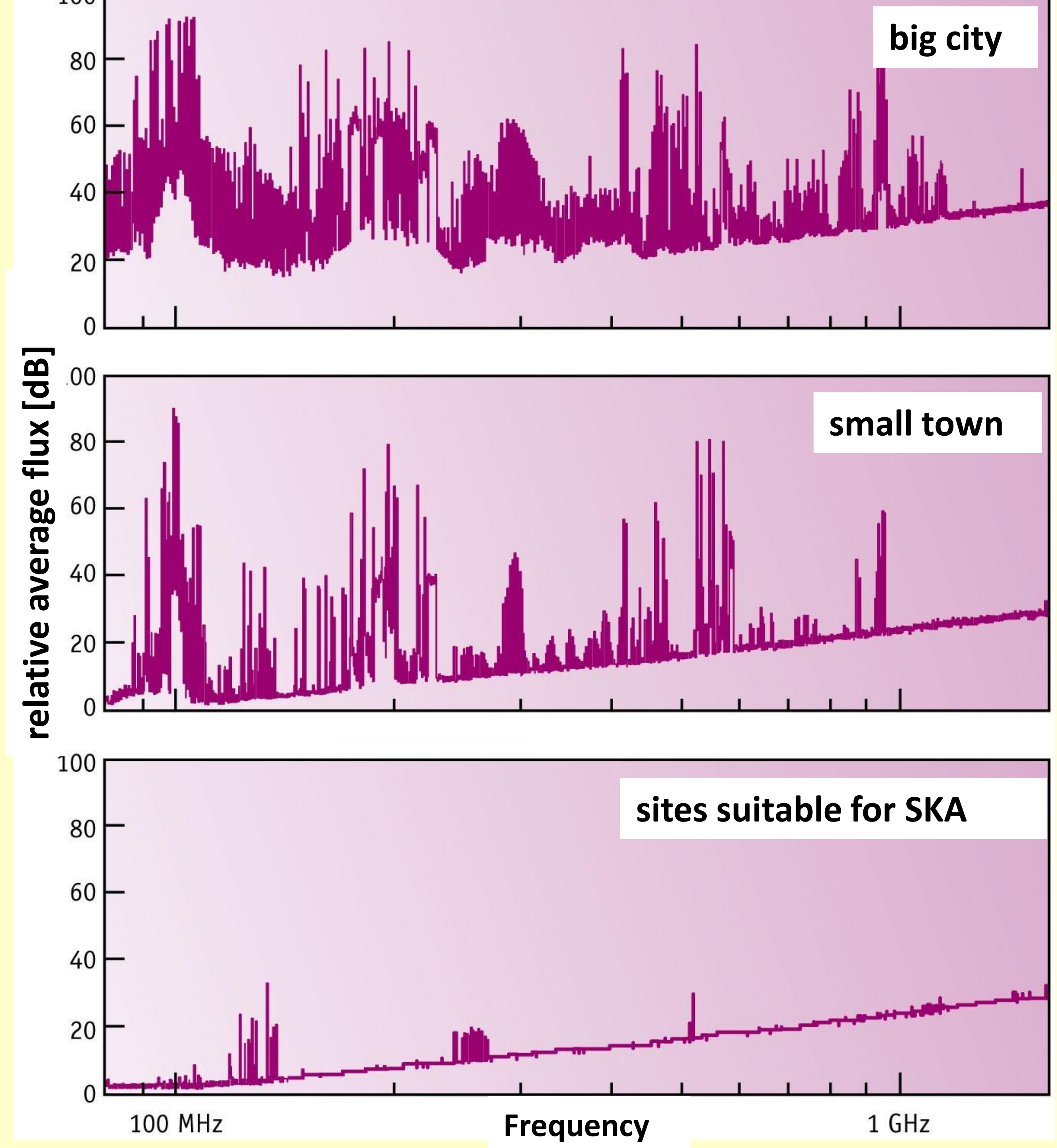
In radio astronomy

Noise

is always a big issue

Problem No.0

human made noise
(= ‘Civilisation’)



Radio interference by human activities (electric power, electronic devices)

➔

search a radio-quiet site

Sources of radio noise

- Radio communications and radio control ➔ reserved frequency allocations for radio astronomy
- … also: harmonic emissions from these transmitters
- Electric power lines: harmonics of 50 Hz go well into LF
- Fluorescent lamps: noise up to HF
- Old television sets and computer screens: harmonics of horizontal sweep oscillator (15625 Hz) cause ‘gurgling’ up to 50 MHz
- Switched power supplies (YOUR computers) make a hash up to 50 MHz
- Pulses from computer circuitry (clocks now near 1 GHz; NB: a pulse with a rise/fall time of 0.1 ns makes noise up to 10 GHz) … weak, but they are there

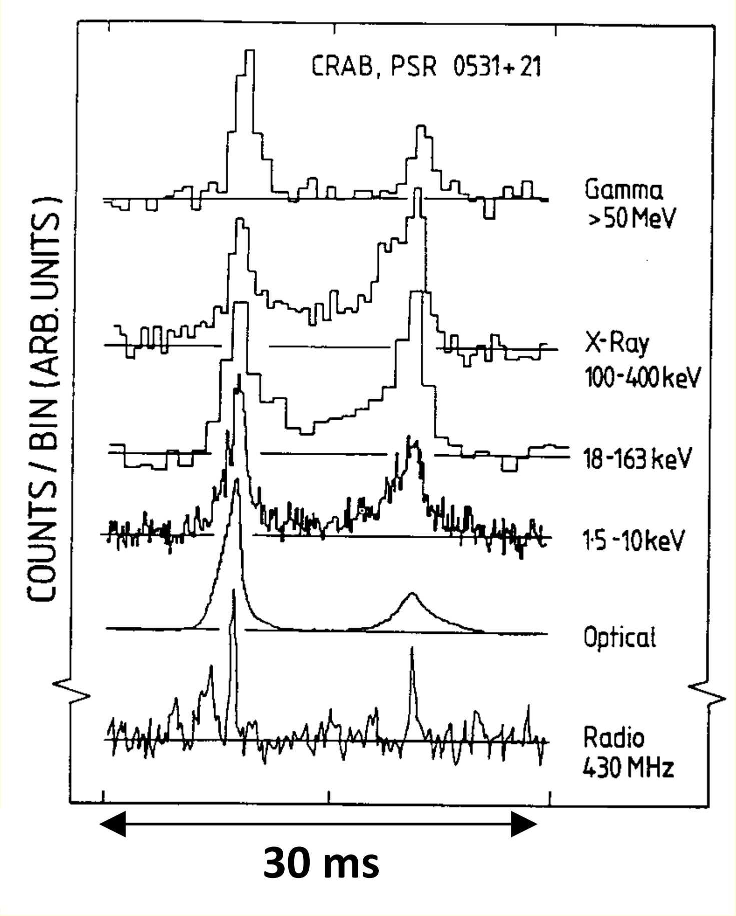
Problem No.1: Noise

- Celestial signals are incoherent (noise-like) signals!

- Usually there is no modulation

  Exception: pulsars!

  the Crab blinks with about 30 Hz ('purrrr') at all frequencies



Quantities (all per unit frequency)

Depends on antenna!

- Power P received by the antenna
- Flux F (or: spectral flux density S)

$$P = A_{eff} * F / 2$$

dipole picks up only linearly polarized radiation!

Unit of flux: 1 Jy = 1 Jansky = 10^{-26} W/m²/Hz

- Intensity I (or: surface brightness B)

$$I = F / \Omega_{source}$$

I leave out the index *f* for frequency

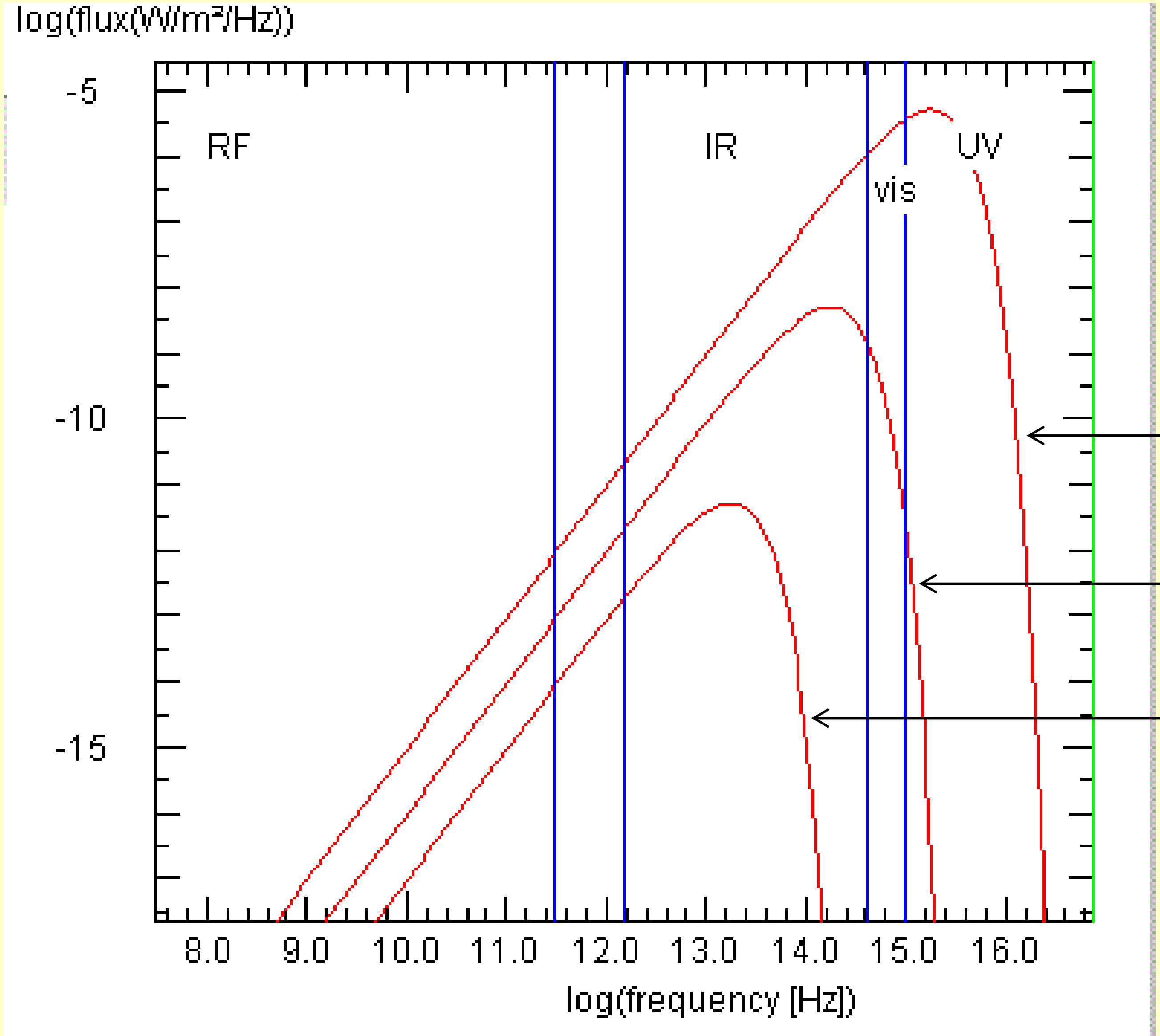
Blackbody radiation (I)

- All bodies (solid … gaseous) emit electromagnetic radiation determined by their temperature
- This is approximately described by the blackbody radiation

$$I_f(f) = B_f(f,T) = \frac{2hf^3/c^2}{e^{hf/kT}-1}$$

is the intensity per unit <u>frequency</u> interval

Blackbody radiation (II)



Temperature

30000 K

3000 K

300 K

Blackbody radiation (III)

- Frequency of intensity maximum (Wien 1894)

$$\frac{hf}{kT} \approx 3$$

- Integral over all frequencies (Stefan 1879, Boltzmann 1884)

$$\pi B = \sigma T^4$$

$\sigma = 5.669 \; 10^{-5}$ erg cm^{-2} s^{-1} K^{-4}

Blackbody radiation (IV)

- At radio frequencies and for most conditions

$$\frac{hf}{kT} \ll 1$$

- Hence one can use the Rayleigh-Jeans approximation

$$B_f(f,T) = \frac{2hf^3/c^2}{e^{hf/kT} - 1} \approx \frac{2kf^2}{c^2}T = \frac{2k}{\lambda^2}\,T$$

- With λ in meters and intensity in Jansky

$$B_f(f,T) \approx \frac{2760}{\lambda^2}\,T$$

Temperatures …

- Antenna Temperature: is the temperature of a resistor giving the same power of thermal noise as the power received by the antenna:

$$P = k\,T_A$$

- Brightness Temperature: the temperature of a body giving the same intensity of thermal noise as the observed (deduced) intensity:

$$I(f) = B(f, T_B) \approx \frac{2760}{\lambda^2}\,T_B$$

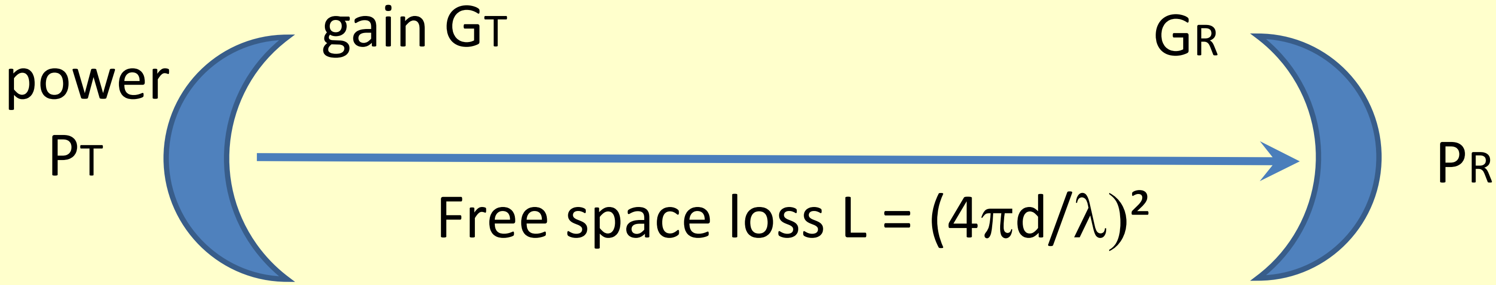
Effective area of an antenna

- Universal formula: $A_{eff} \approx gain * \lambda^2/4\pi$

- Single half-wave dipole: $A_{eff} \approx 0.13\ \lambda^2$
- Yagi-Uda or Helix: $A_{eff} \approx gain * \lambda^2/4\pi$
- Parabolic dish $A_{eff} \approx \pi\ (diametre/2)^2$
- Large array of antennas $A_{eff} \approx$ physical area

Efficiency = A_{eff} / A_{geom} = 0.5 … 0.9

Communications link: Friis' formula



Power received: $P_R = \underbrace{P_T * G_T}_{} * G_R / L$

= EIRP (effective isotropic radiated power)

e.g. the sun: $P_T = 4\pi R_\odot^2 * \pi B(T_\odot)$ $G_T = 1$ (isotropic)

rec.antenna $G_R = 4\pi A_{eff}/\lambda^2$

$$P_R = \pi B(T_\odot)\, 4\pi R_\odot^2 * 4\pi\, A_{eff}/\lambda^2 * (\lambda/4\pi d)^2$$

$$= \pi B(T_\odot) * R_\odot^2/d^2 * A_{eff}$$

geometr.dilution

flux F

Friis' formula

- Flux at receiver

  $F = P_R/A_{eff} = EIRP/L * G_R/A_{eff} = EIRP/4\pi d^2$

- i.e. EIRP = luminosity

- N.B.: L would also include other propagation losses (ionosphere, atmosphere, …)

Friis' formula in dB

- $P_R = P_T + G_T + G_R + L$
- ESA-Dresden: f = 12 GHz, G = +42 dB
  - TV satellite (bandwidth 10 MHz):
    - EIRP = +52 dBW
    - d = 36000 km ➔ L = -205 dB
    - ➔ P_R = +52+42-205 = -111 dBW = -81 dBm = +29 dBμV
  - Sun (T=12000 K, R=7 10^8 m, cont.➔ 1Hz BW)
    - EIRP = +40 dBW/Hz
    - d = 1 AU = 1.5 10^{11} m ➔ L = -278 dB
    - ➔ P_R = -195 dBW/Hz, F = 3.6 10^6 Jy

Detection?

- Depends on Signal-to-Noise ratio S/N because there is no receiver or no system which does not produce noise on its own!
- While a daring optimist might accept $S/N = 1$ for a detection, a more cautious person would demand at least $S/N > 3$ or more if faced with a crucial situation or to be absolutely sure!

What determines the detection limit? … Noise!

- The **receiver** produces thermal noise
- The **antenna** receives thermal noise from the sidelobes (ground clutter, spill-over)
- The **sky** has some thermal emission (Earth atmosphere)
- The **3K cosmic microwave background**

Thermal noise

Power emitted in bandwidth Δf:

$$P = kT\,\Delta f$$

Room temperature T_o = 290 K:

$$kT_o = 4.00\;10^{-21}\ \text{W/Hz} = -204\ \text{dBW/Hz}$$

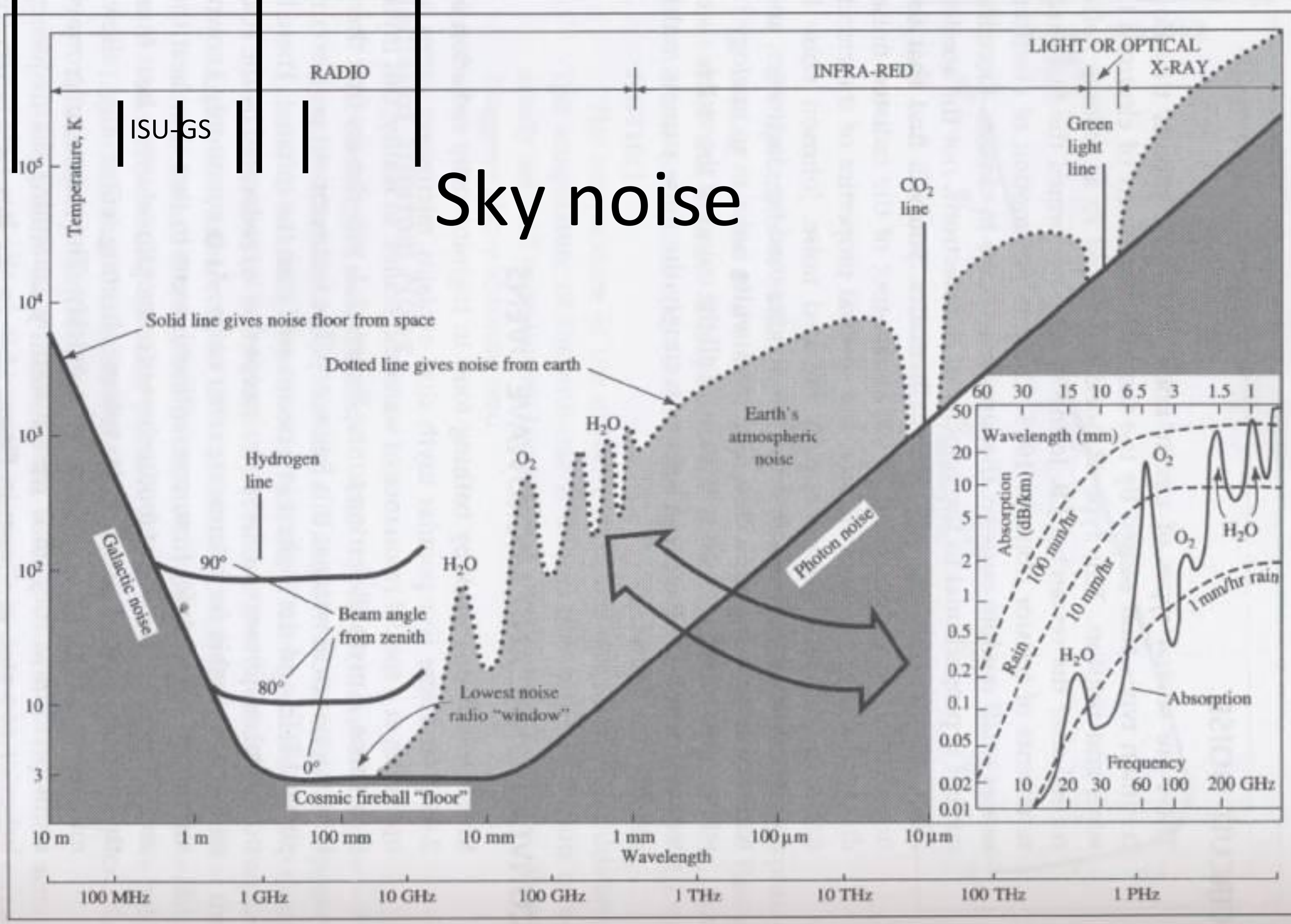
Hence:

- Satellite (single signal in 8 MHz receiver BW):
  - signal = -111 dBW
  - noise = -204 dBW/Hz + 69 = -135 dBW
  - S/N = -111 + 135 = + 24 dB
- Sun (continuum):
  - signal = -195 dBW/Hz
  - noise = -204 dBW/Hz
  - S/N = + 9 dB

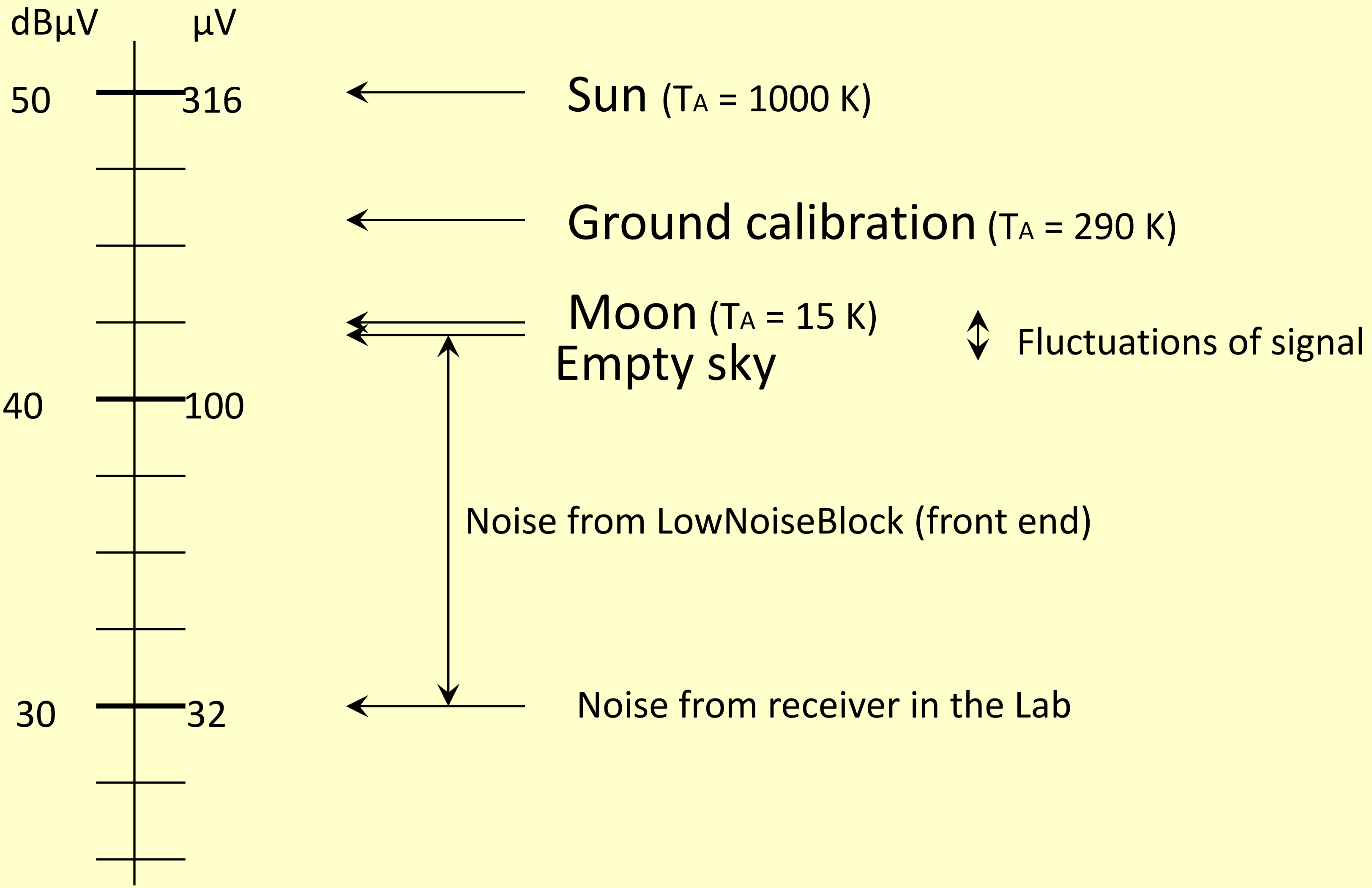
RadioJove ESA-Haystack ESA-Dresden

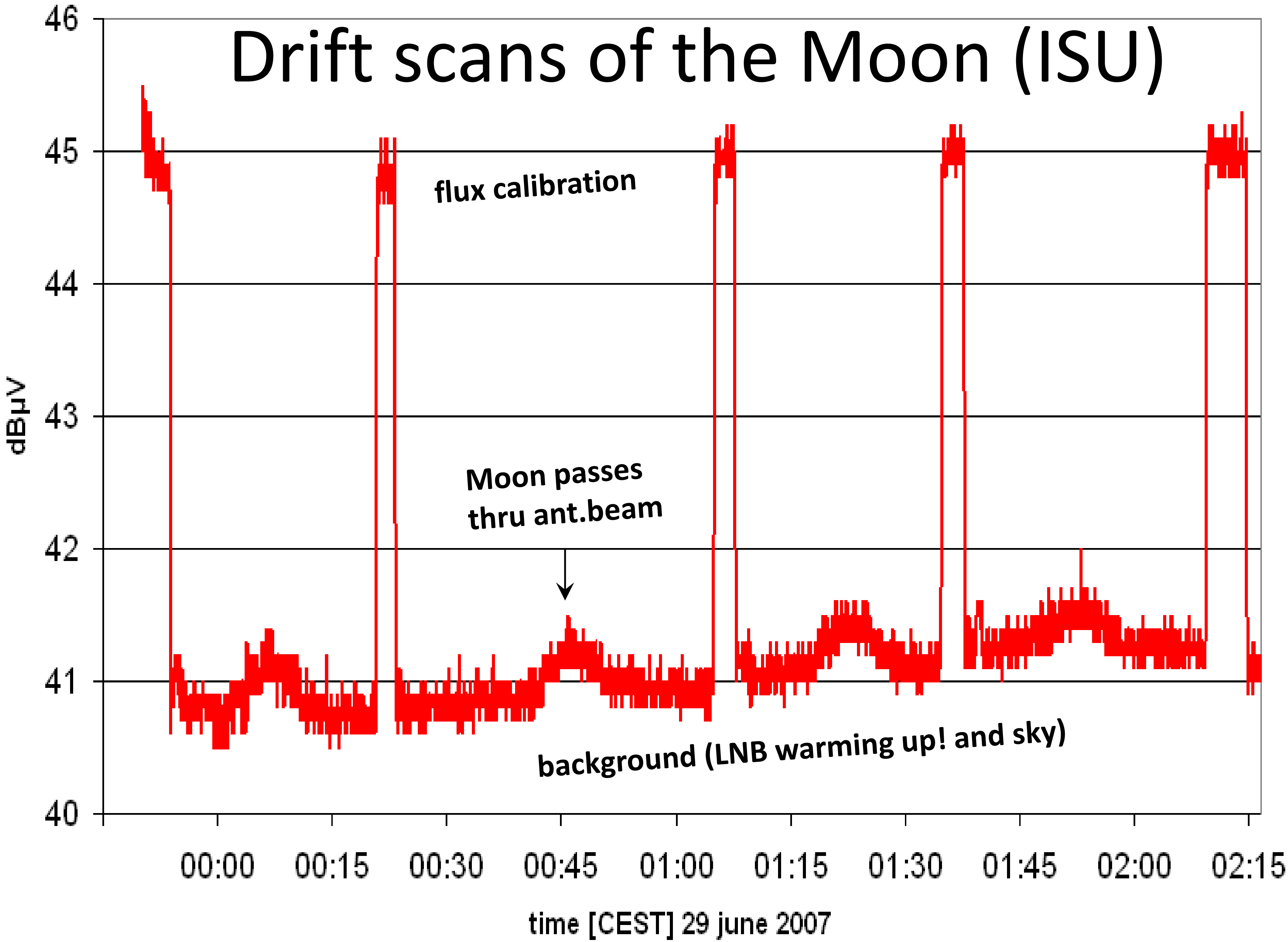
ISU-GS

Sky noise



For example: ISU's ESA-Dresden radio telescope ($A_{eff} = 0.84\ m^2$)




Drift scans of the Moon (ISU)
flux calibration
Moon passes
thru ant.beam
background (LNB warming up! and sky)
dBμV
46
45
44
43
42
41
40
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:15
time [CEST] 29 june 2007

System Temperature

- Power received is sum of external signal and internal noise; write in **antenna** temperatures:

$$T_{ON} = T_{source} + T_{sys}$$

- Compare with measurement of `empty' sky :

$$T_{OFF} = T_{sky} + T_{sys}$$

$$Y = P_{ON}/P_{OFF} = T_{ON}/T_{OFF} = (T_{source} + T_{sys}) /(T_{sky} + T_{sys})$$

System Temperature

- (For our small telescopes, we may neglect contributions from 3K cosmic microwave background and earth atmosphere: $T_{sky} = 0$)
- T_{sys} contains all the noise contributions of receiver, antenna spill-over, feeder losses …

- Detection threshold: e.g. $T_{ant} > 0.1\ T_{sys}$

System temperature

- We measure it by comparing the calibrator (= ground @ 290 K) with the `empty' sky:

$$T_{sys} = T_{cal}/(Y-1) = T_{cal}/(T_{ON}/T_{OFF}-1)$$

- ESA-Dresden: calibrator = Holiday Inn hotel
  ➔ T_{sys} = 170 K
- ESA-Haystack: calibrator = ISU library wall
  ➔ T_{sys} = 300 K

Sensitivity of a Telescope

- Detection limit: T_{ant} = 20 K

  $P = k * T_{ant} = A_{eff} * F / 2$ gives

  $F_{min} = 2\ k\ T_{ant} / A_{eff}$

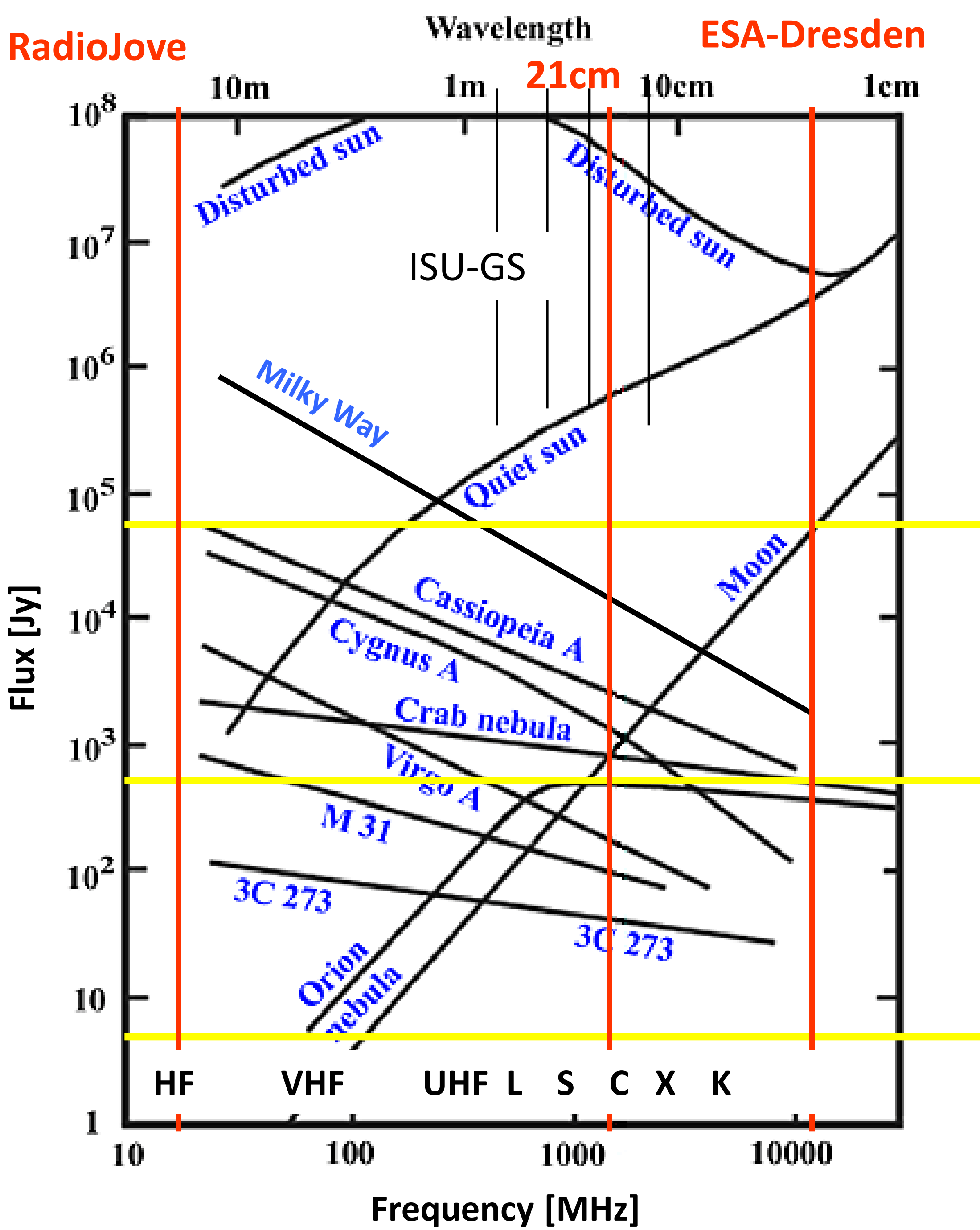
- For $A_{eff} = 1 m^2$:

  $F_{min} = 2 * 1.38\ 10^{-23} * 20 / 1$ Ws/m^2

  $= 5.5\ 10^{-22}\ W/m^2/Hz$

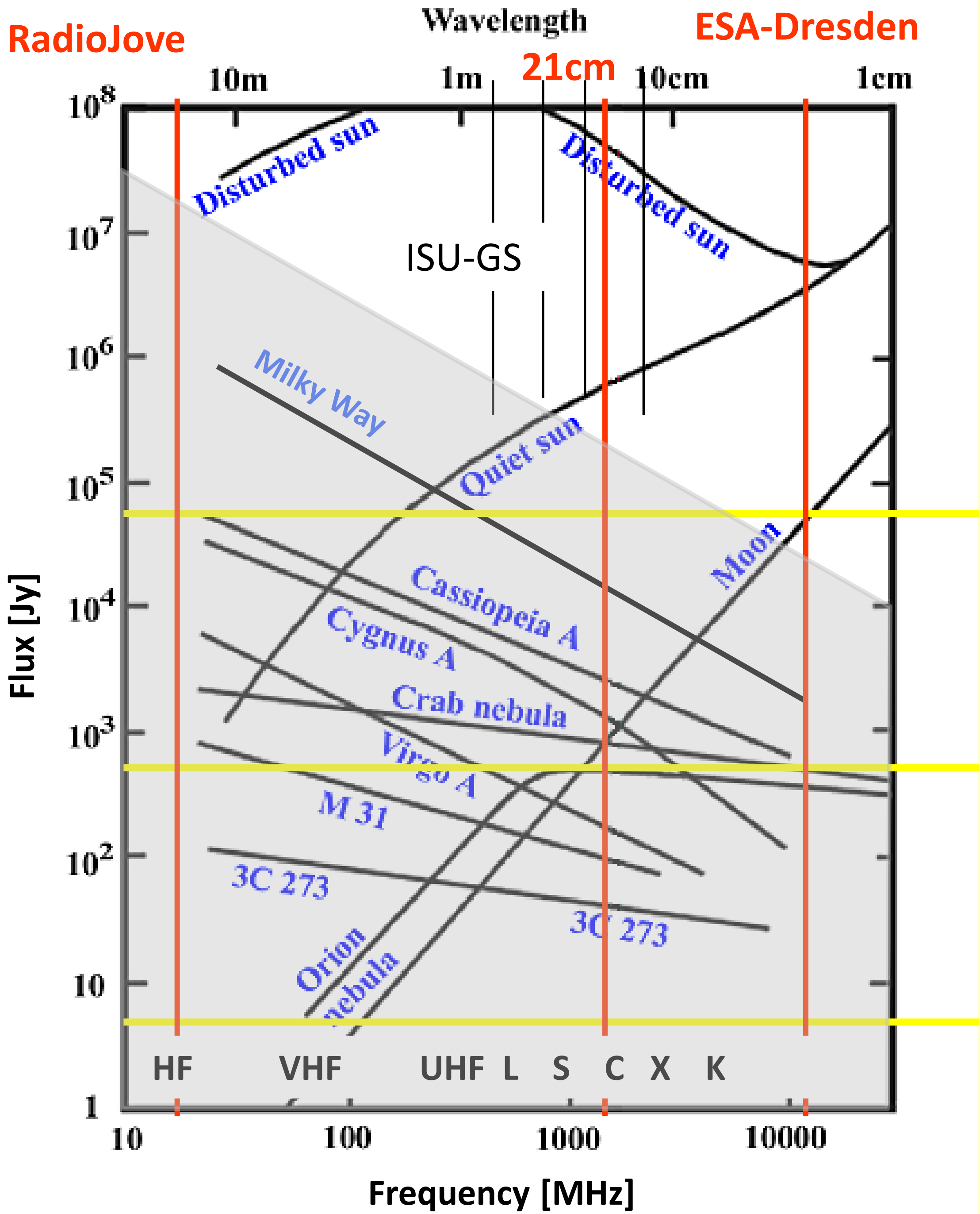
  = 55000 Jy

- Lower T_{ant} threshold ← clever techniques ...



Antenna diameters for detection with T_{ant} = 20 K

1 m	ESA-Dresden
2 m	ESA-Haystack
10 m	DSN
100 m	Jodrell Bank, Effelsberg, GBT, Arecibo



The measured external noise on Illkirch Campus …

Antenna diameters for detection with T_{ant} = 20 K

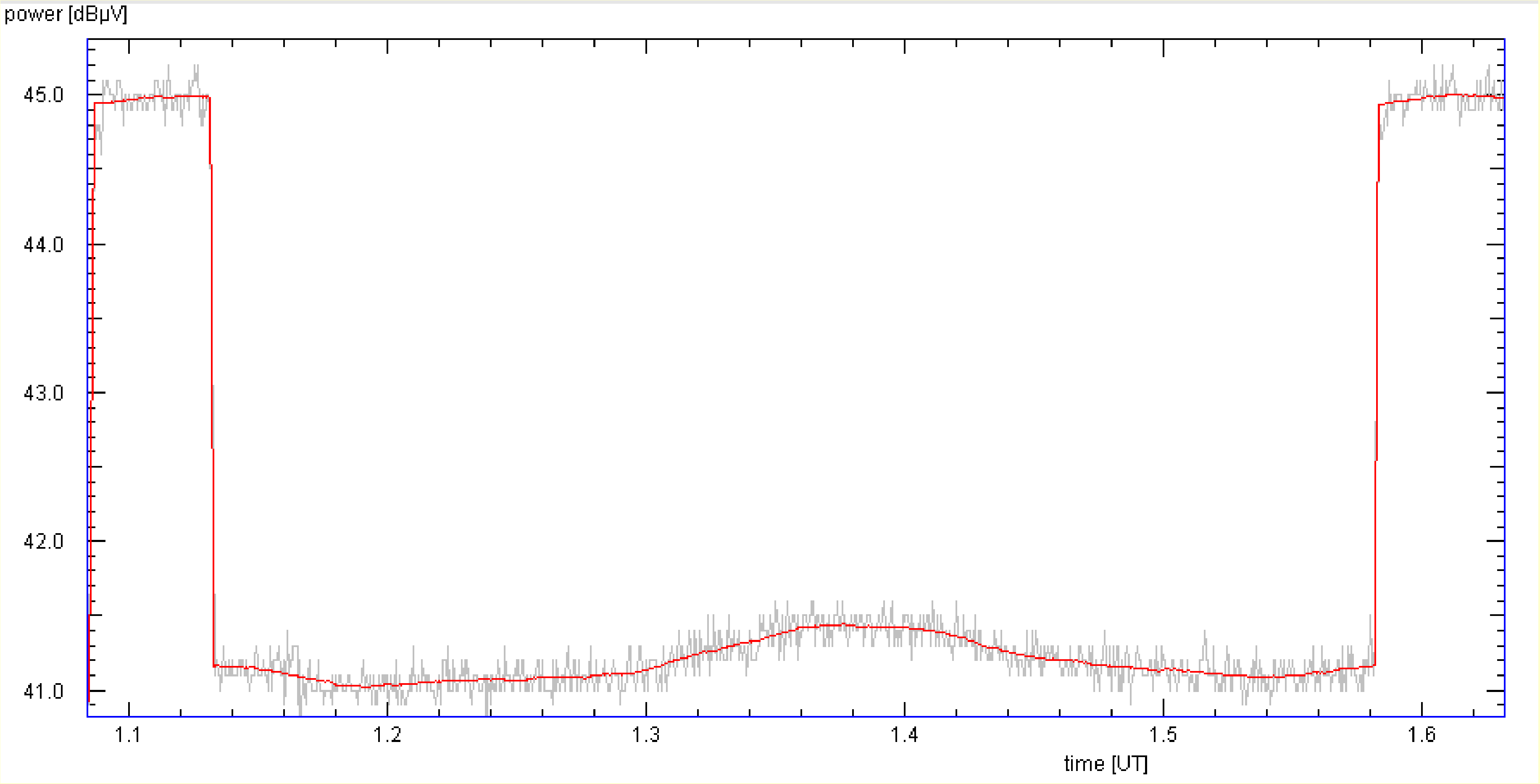
1 m	ESA-Dresden
2 m	ESA-Haystack
10 m	DSN
100 m	Jodrell Bank, Effelsberg, GBT, Arecibo

How to beat noise: Integration

- Longer observation time ➔ larger sample
- measurement = true value + noise $x_i = a + r$ (r random variable ~ Gauss(0, σ_0))
- Average value $\bar{x} = \frac{1}{n} \sum x_i$
- Variance $\sigma^2 = \frac{1}{n} \sum (x_i - \bar{x})^2 = \overline{x^2} - \bar{x}^2$ ➔ σ_0
- Average is distributed like Gauss(a, $\sigma/\sqrt{n}$)

  ➔ Error bar decreases with sample size!

Smoothing



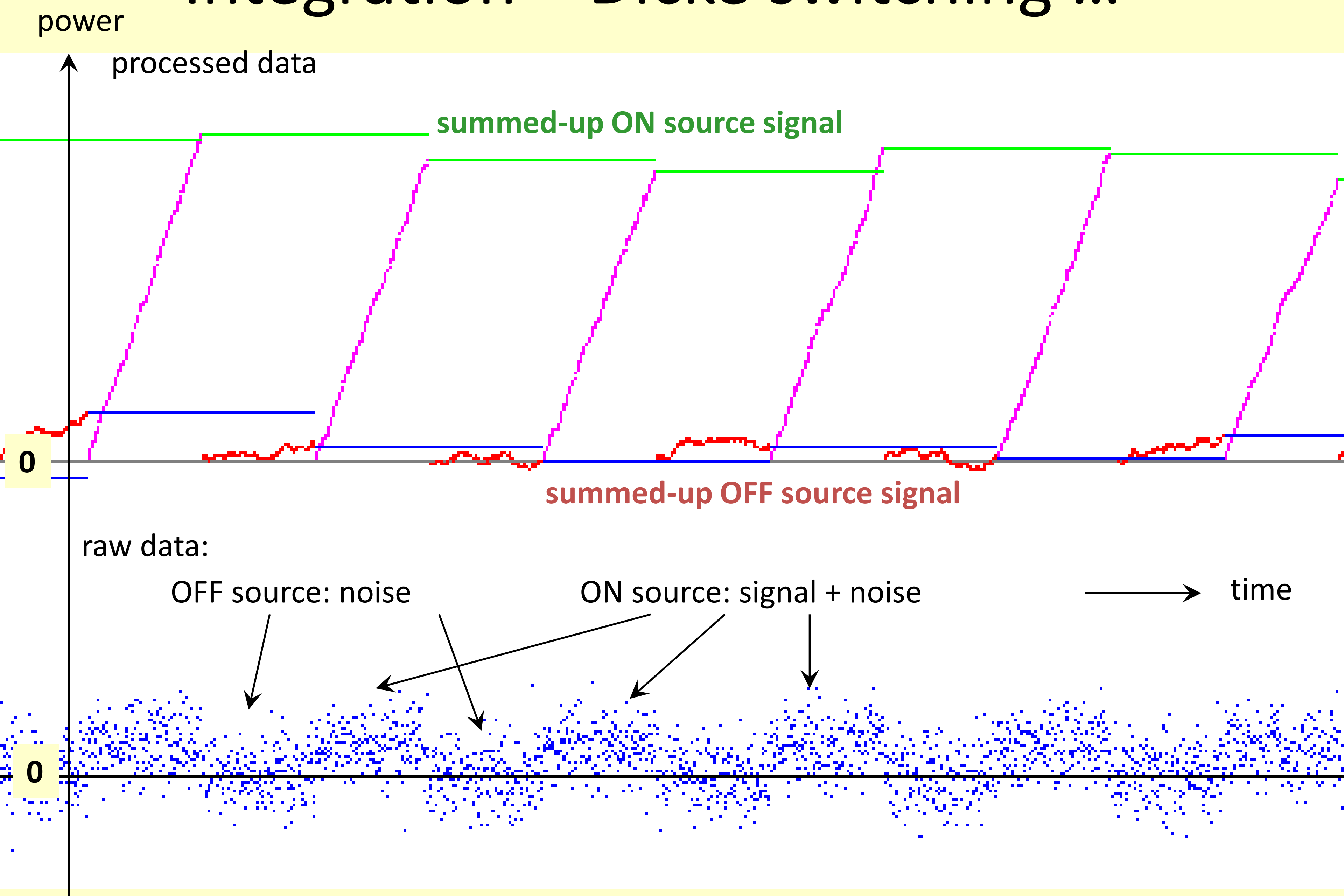
running boxcar average over 30 data points

How to beat noise: Switching

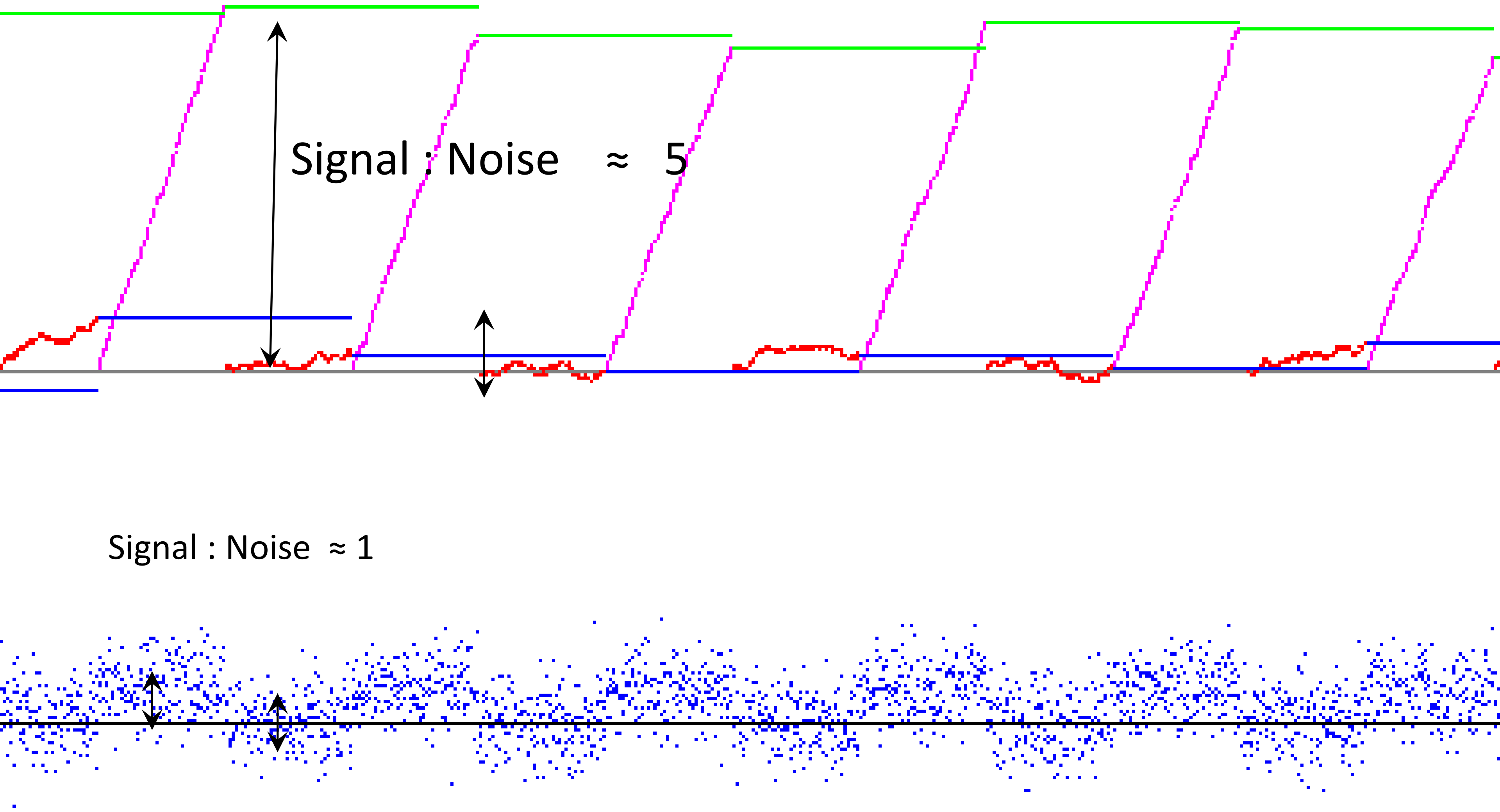
- switch periodically between the object and (stable) comparison source:
  - terminating resistor (thermal noise; Dicke)
  - `empty' sky (beam switching, moving secondary mirror)

- Lines: compare with nearby (`empty') continuum

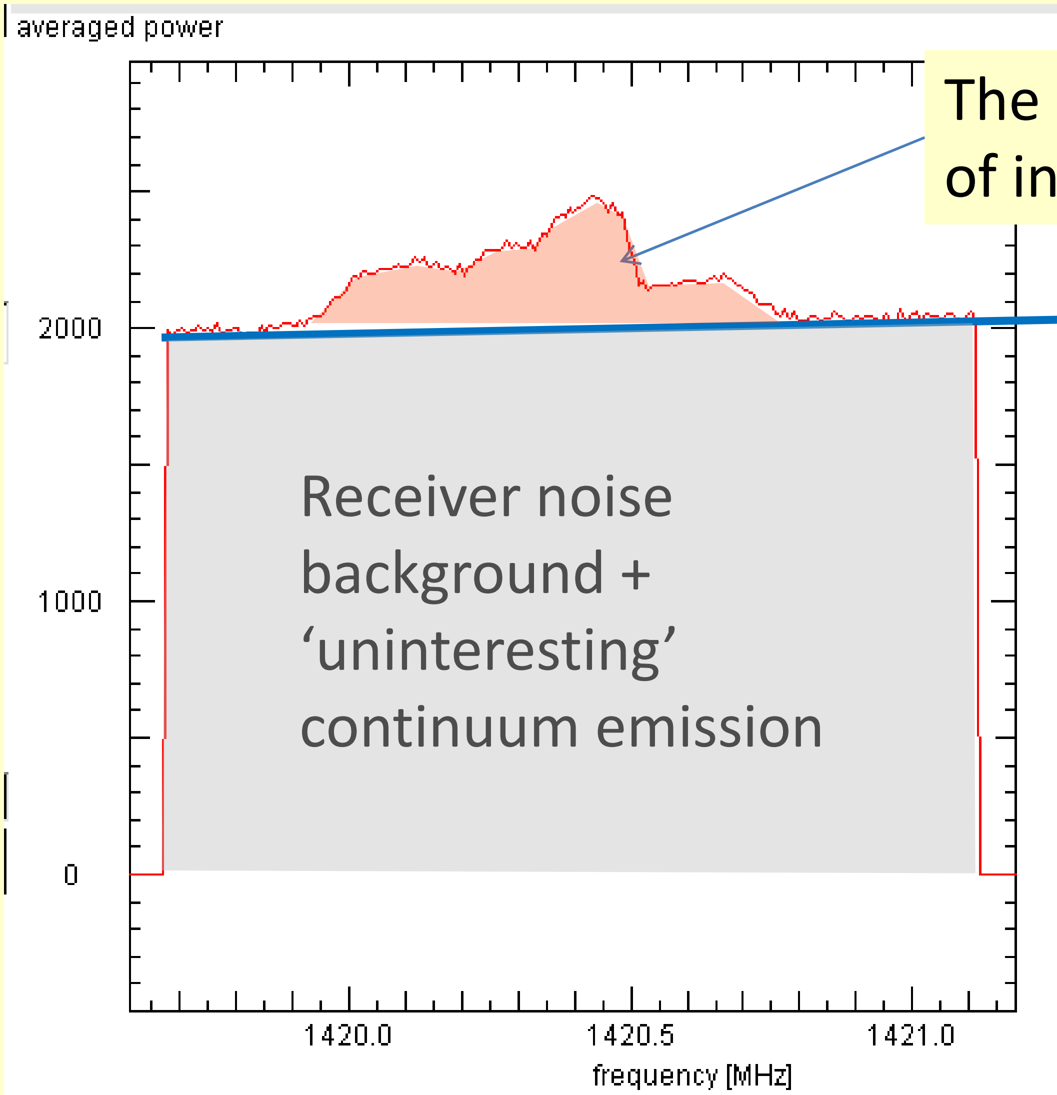
Integration + Dicke switching …



… improves the S/N ratio

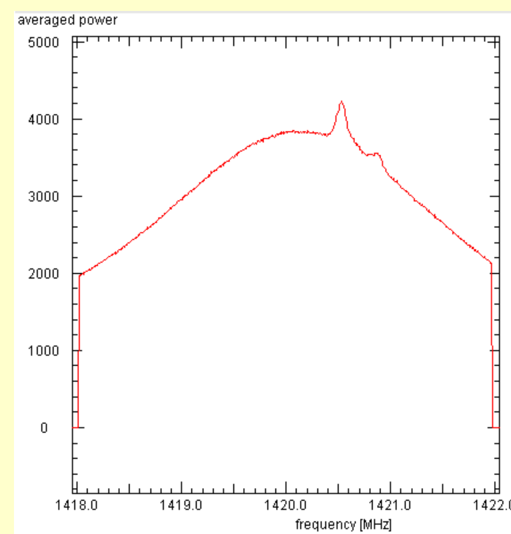


Lines: compare with nearby continuum

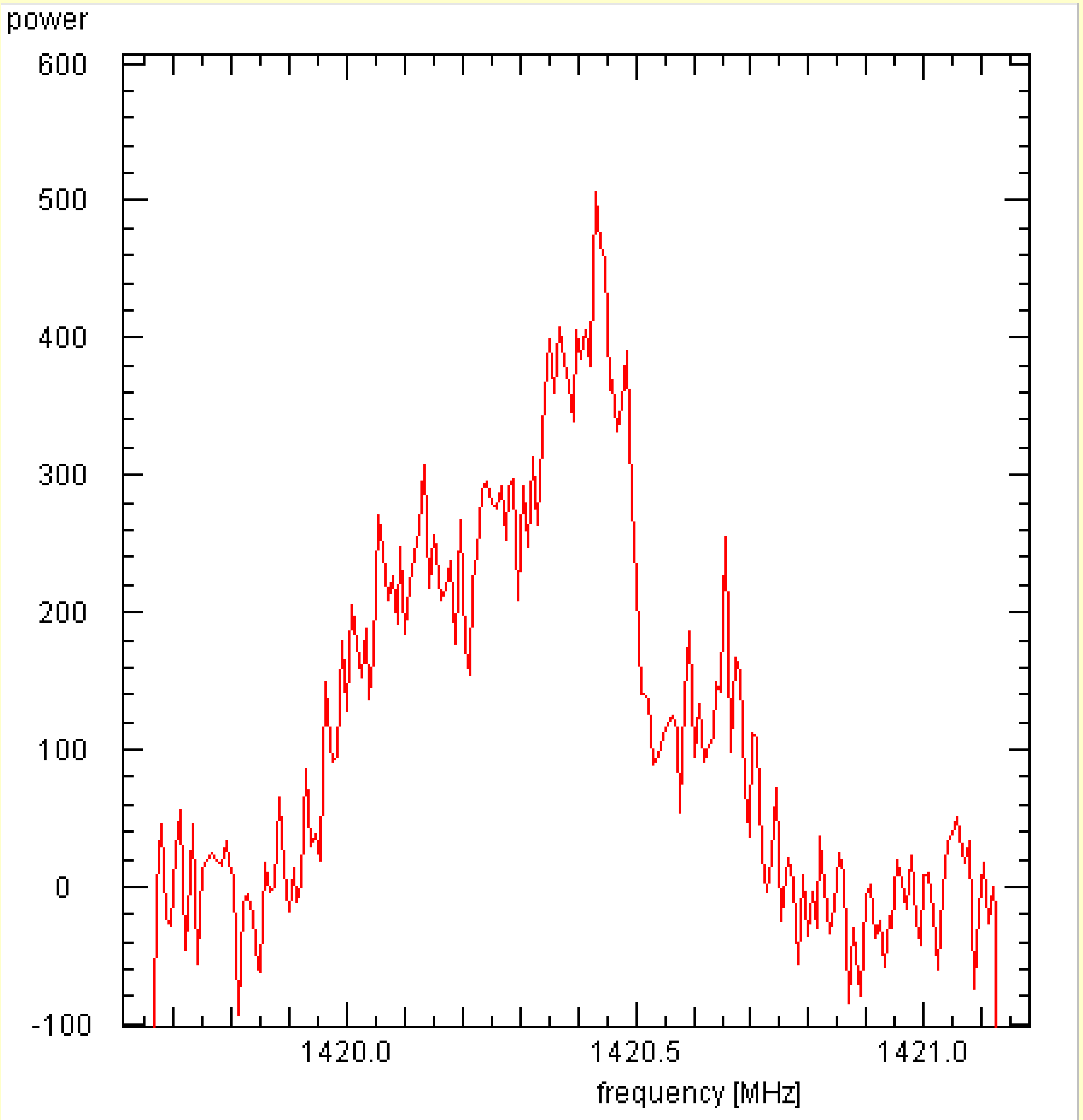


The line emission feature of interest

The **baseline** = the neighbouring continuum, i.e. free of line emission (assume e.g. linear shape…)

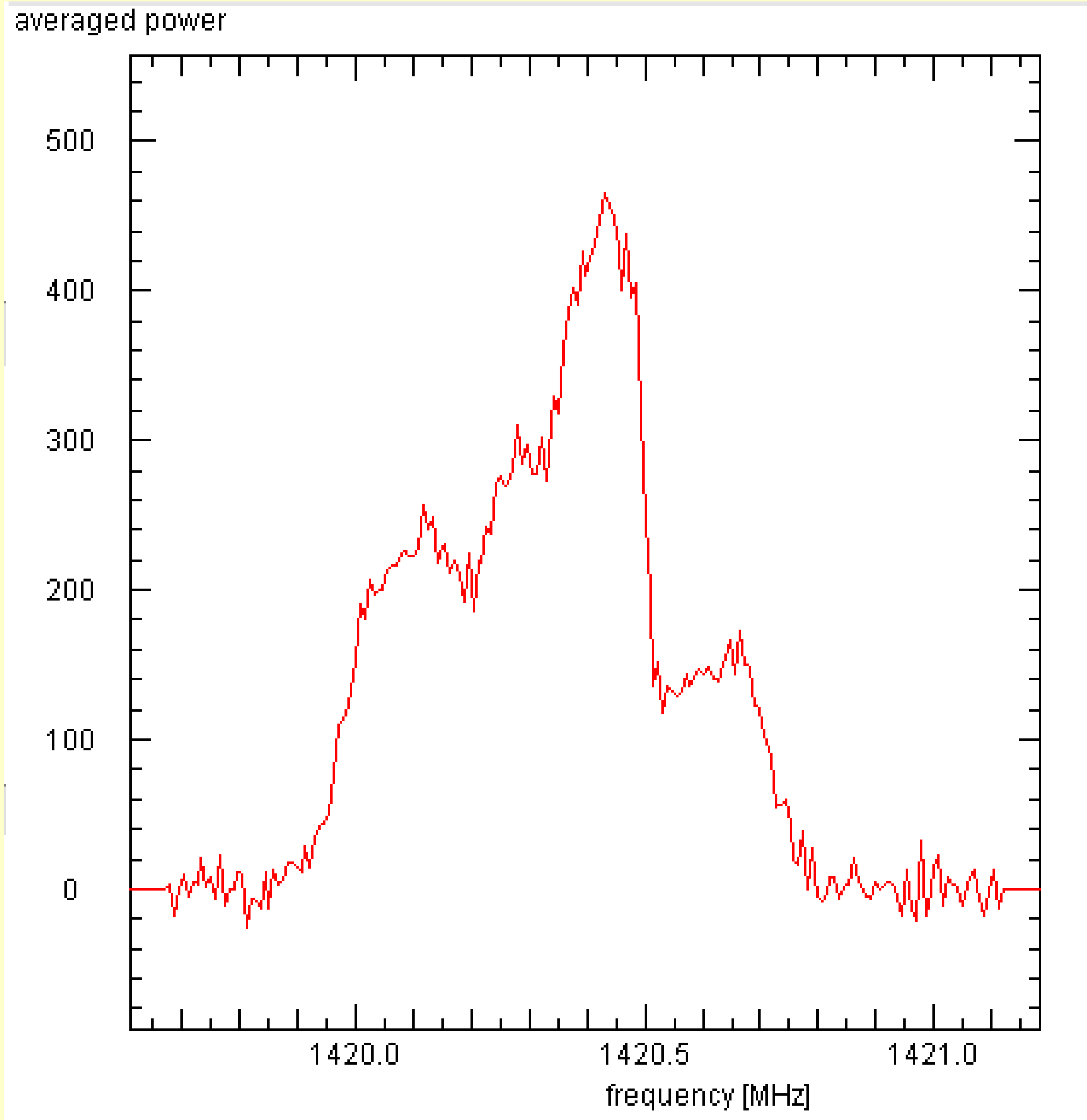


Subtract the baseline …

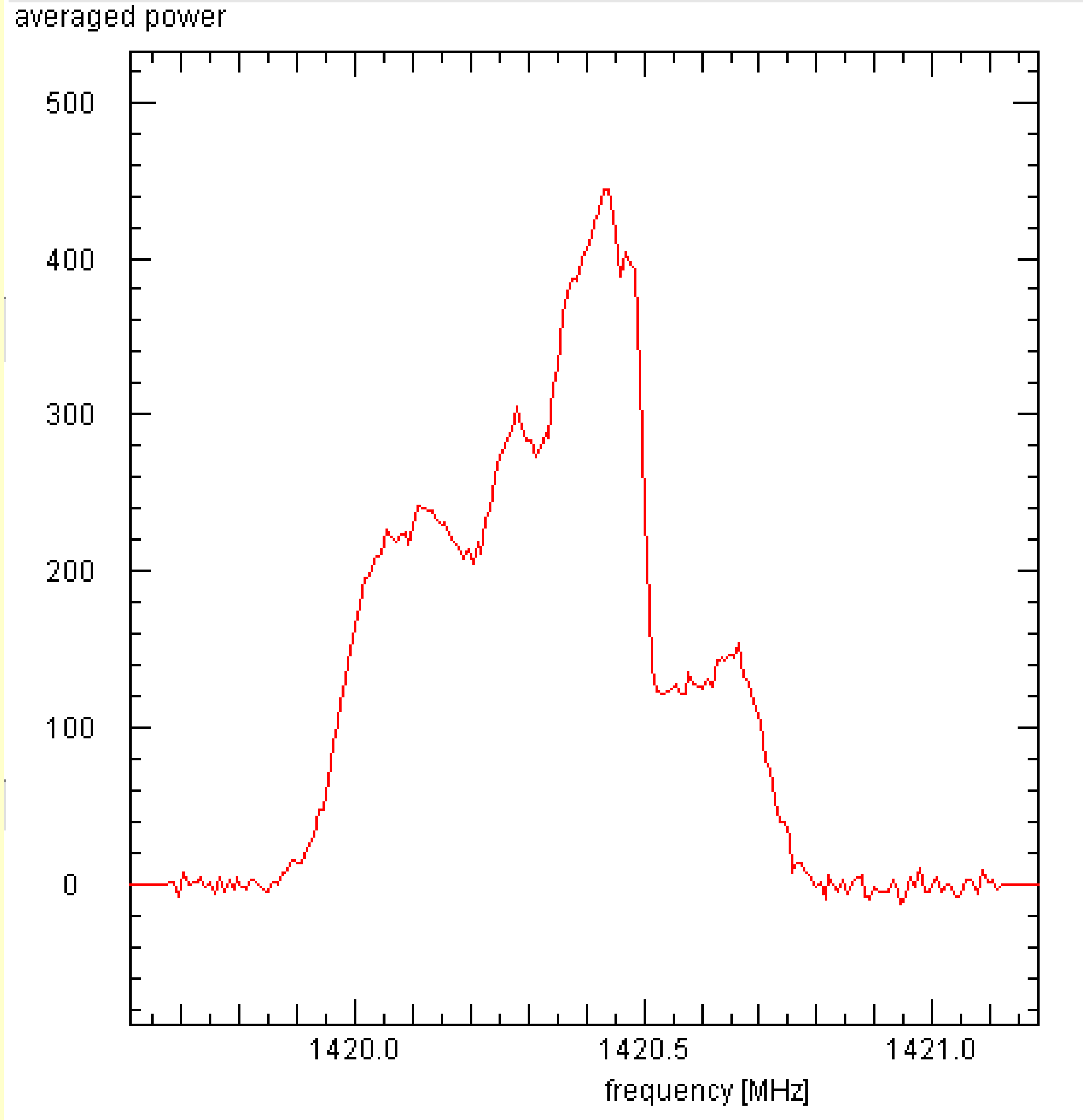


… and get the line emission:

1 spectrum


averaged power
500
400
300
200
100
0
1420.0
1420.5
1421.0
frequency [MHz]

10 spectra



averaged power
500
400
300
200
100
0
1420.0
1420.5
1421.0
frequency [MHz]

54 spectra