Calibration Techniques

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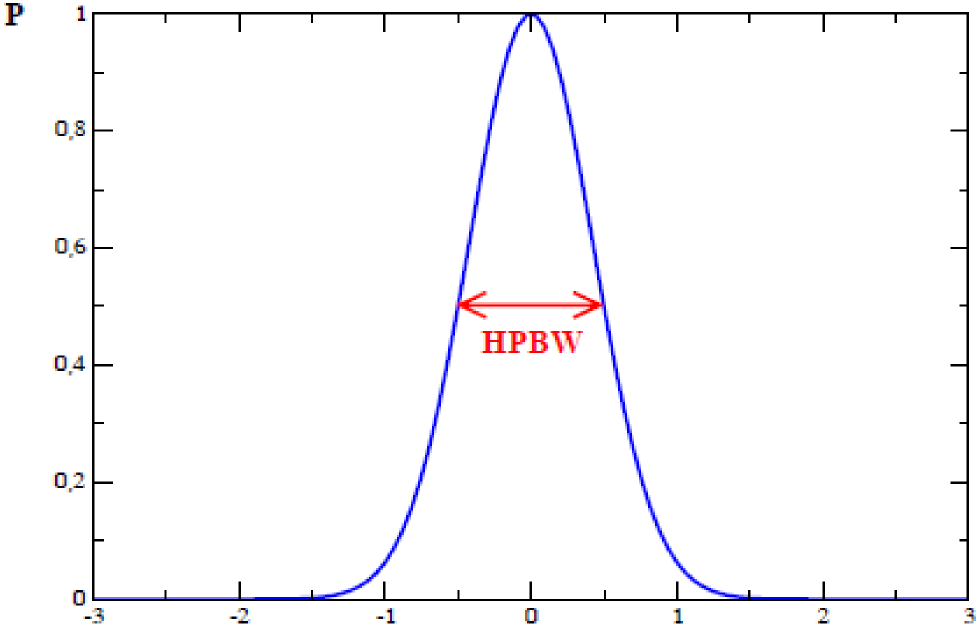
Content

- What do we receive?
- What is contributing to the overall noise?
- How does the calibration actually work?
  - Counts to T_{ant}
  - Opacity correction
  - Gain elevation effects
  - From Kelvin to Jansky

Measuring sources

- The main beam *B* of a radio telescope is well described by a Gaussian with a Half Power Beam Width Θ_{HP}:

$$B = \exp\left[-4\ln 2\left(\frac{\Theta}{\Theta_{HP}}\right)^2\right], \qquad \Theta_{HP} \approx 1.2\frac{\lambda}{D}$$



e.g. for Effelsberg 100m:

at λ = 6cm: Θ_{HP}~150”

at λ = 3mm: Θ_{HP}~10”

Measuring sources II

- The signal received is a convolution of the source structure and the antenna beam

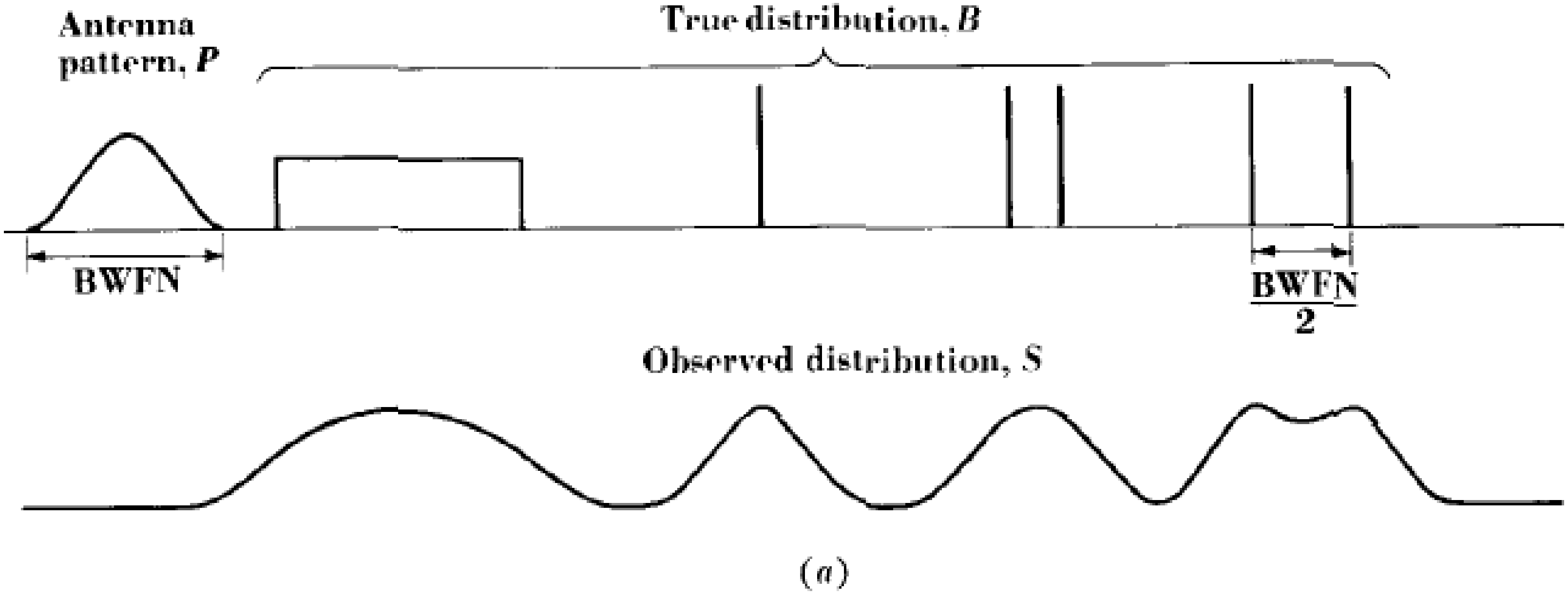
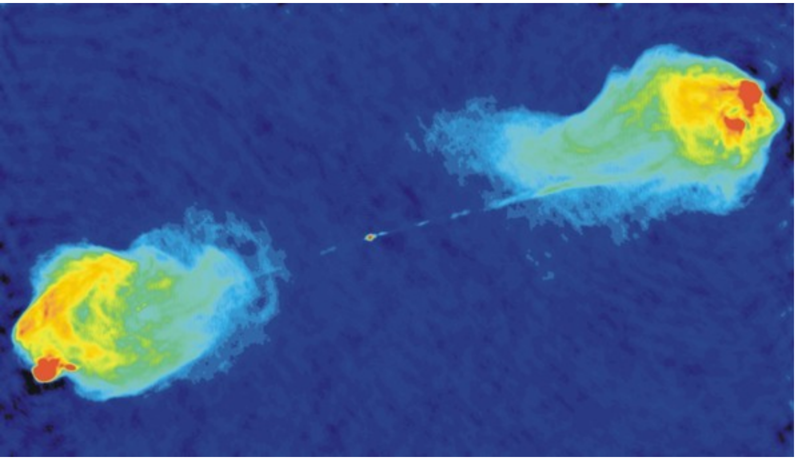


Fig. 6-11a. Smoothed distribution S observed with antenna pattern P.

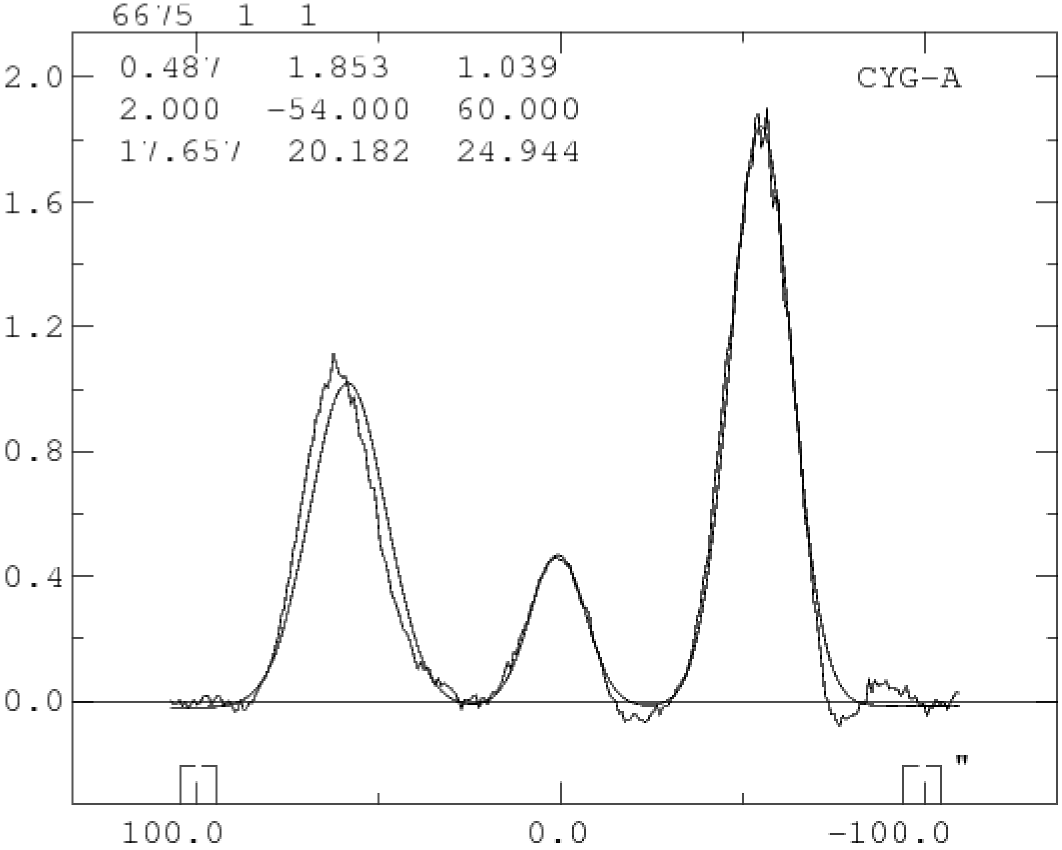
(J.D. Kraus: Radio Astronomy)

Measuring sources III

- Cyguns A, extend ~2', at 7mm at ~20“ resolution.



VLA image. Courtesy of NRAO/AUI; R. Perley, C. Carilli & J. Dreher



Measureing sources III

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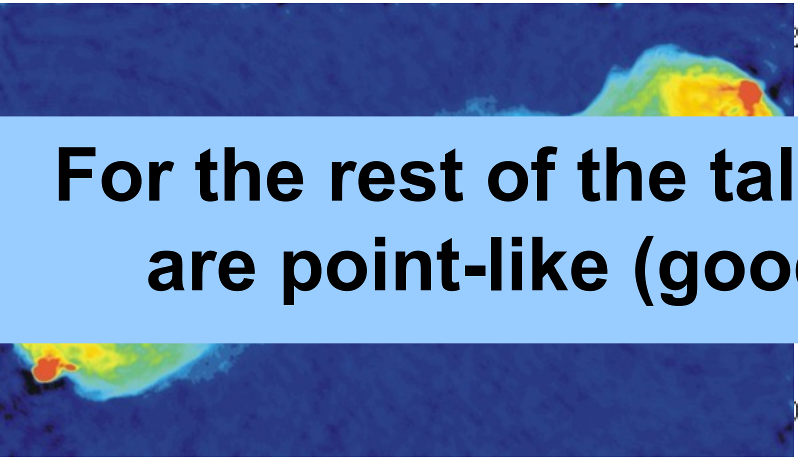
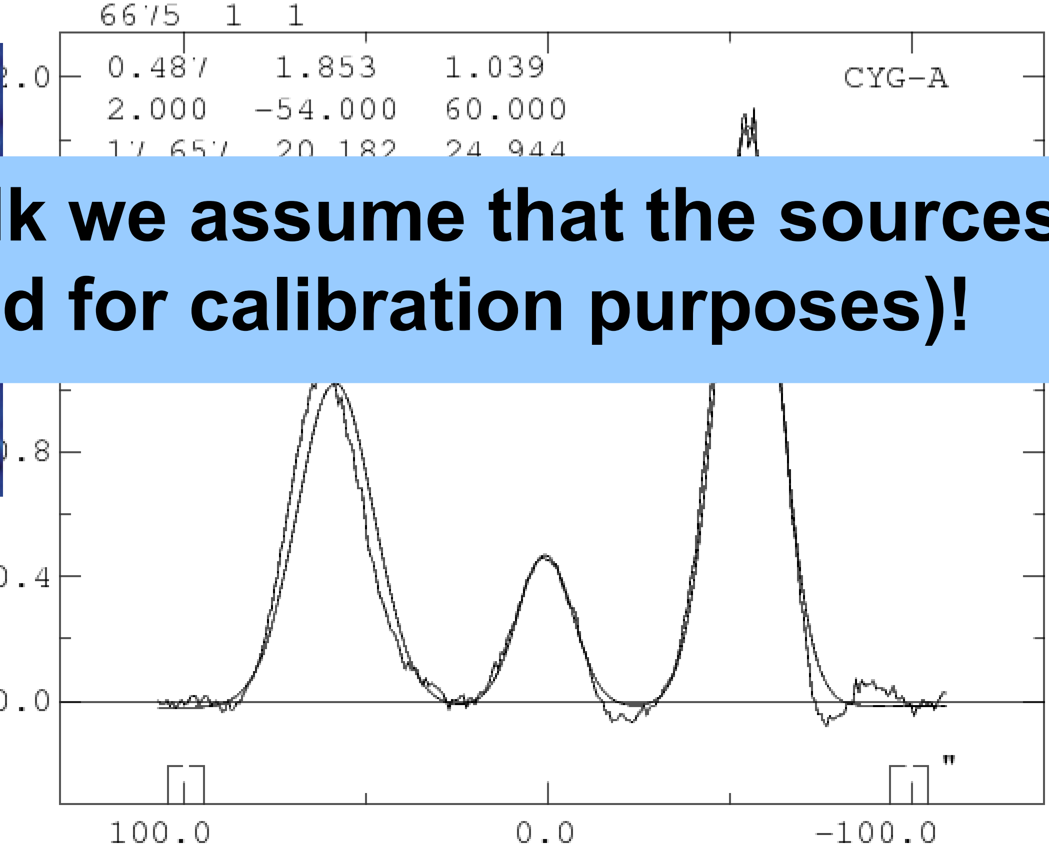




For the rest of the talk we assume that the sources are point-like (good for calibration purposes)!

VLA image. Courtesy of NRAO/AUI; R. Perley, C. Carilli & J. Dreher

Received Power

- The received power is a function of
  - The source flux density S (1Jy=10^{-26}Wm^{-2}Hz^{-1}).
  - The collecting area A_{geom} (geometric aperture).
  - The aperture efficiency η_A.
  - The bandwidth $\Delta\nu$.

→ $P = 0.5 \cdot S \cdot A_{eff} \cdot \Delta\nu$, where $A_{eff} = \eta_A \cdot A_{geom}$

Antenna Temperature

Due to the equivalent of power and temperature

$$\boxed{P = k \cdot T \cdot \Delta\nu}$$

a radio source with flux density S has a corresponding **antenna temperature**

$$\boxed{T_{src} = S \cdot A_{eff} / (2 \cdot k)}$$

Antenna Temperature II

$T_{src} = S \cdot A_{eff} / (2 \cdot k)$

- Define the **sensitivity** Γ of an antenna

$$\Gamma = \frac{T_{src}}{S} \quad [K/Jy]$$

$$\Gamma = \frac{A_{eff}}{2 \cdot k} = \eta_A \frac{A_{geom}}{2 \cdot k} = \eta_A \frac{\pi \cdot D^2}{8 \cdot k}$$

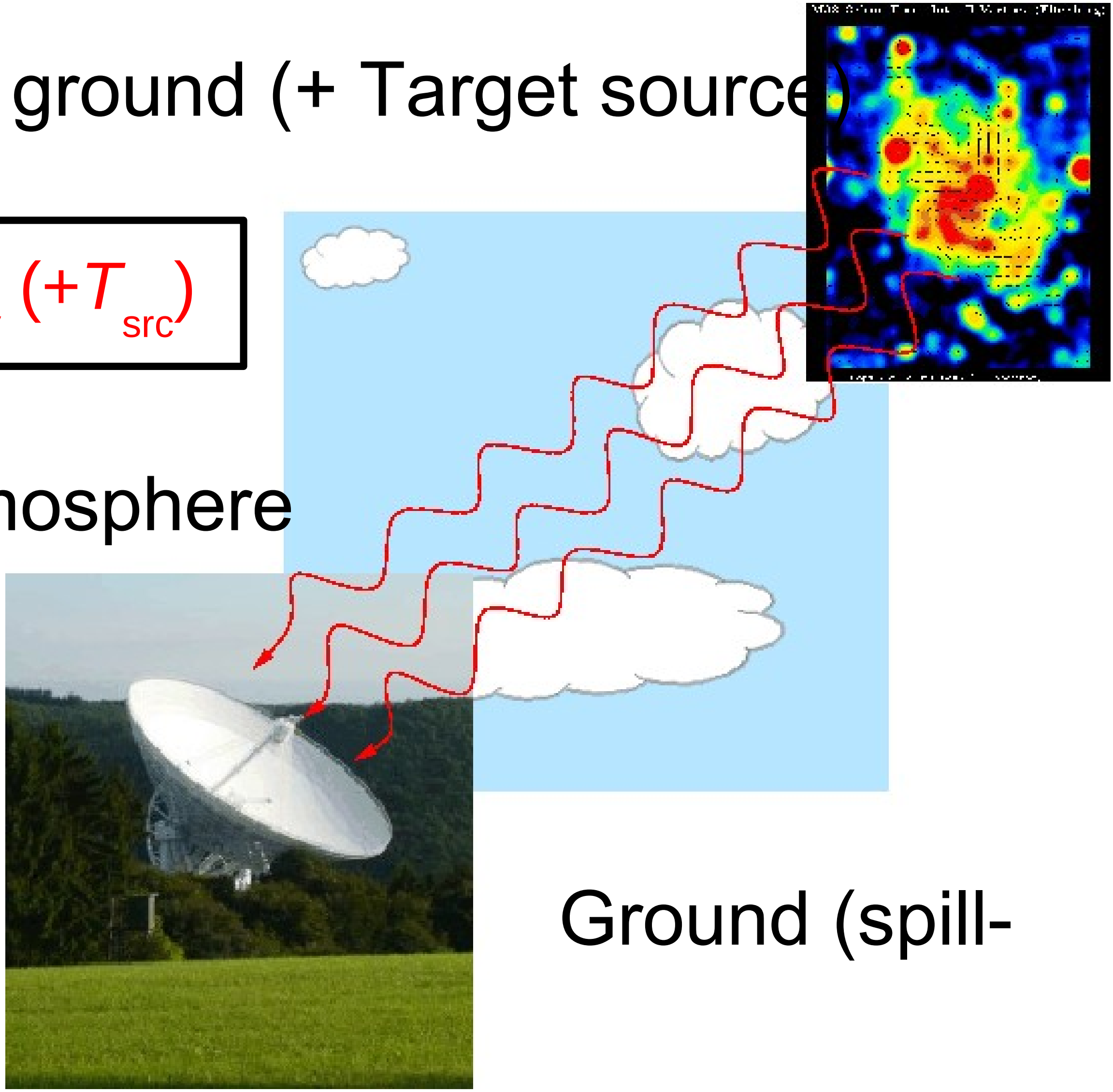
- The aperture efficiency η_A depends on wavelength λ, surface accuracy σ, aperture blocking, …

For Eb (100m): $T_{src} / S = \Gamma = \eta_A$ 2.84 K/Jy

For a 25m dish: $\Gamma = \eta_A$ 0.18 K/Jy

Sources of noise

$$T_{sys} = T_{rec} + T_{ground} + T_{sky} \ (+T_{src})$$



Back ground (+ Target source)

Atmosphere

Receiver

Ground (spill-over)

System Temperature

$$\boxed{T_{sys} = T_{receiver} + T_{ground} + T_{sky}\ (+T_{src})}$$

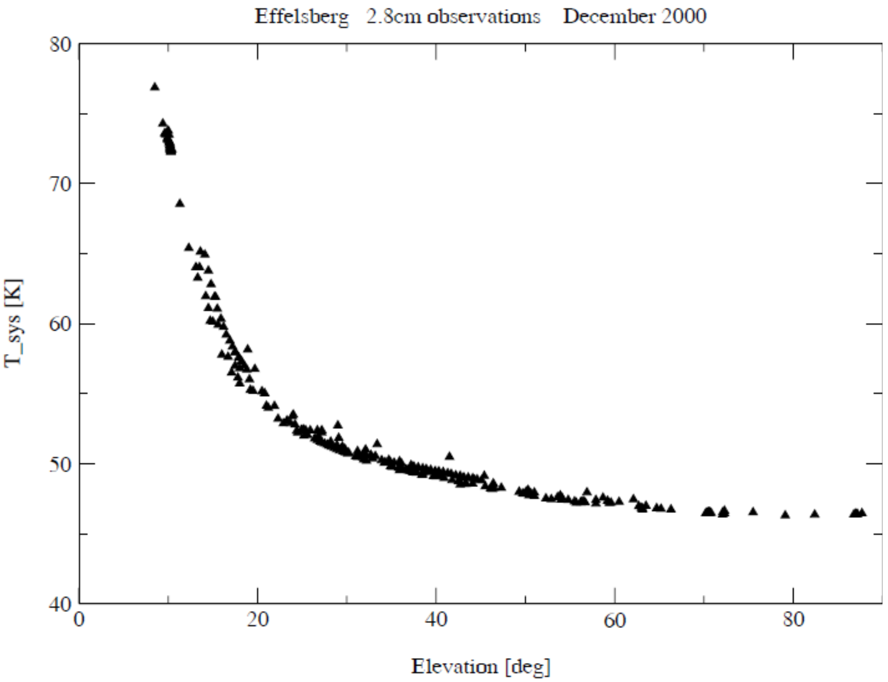
$T_{receiver}$: ranges from a few to several tens of K (cooled receivers).

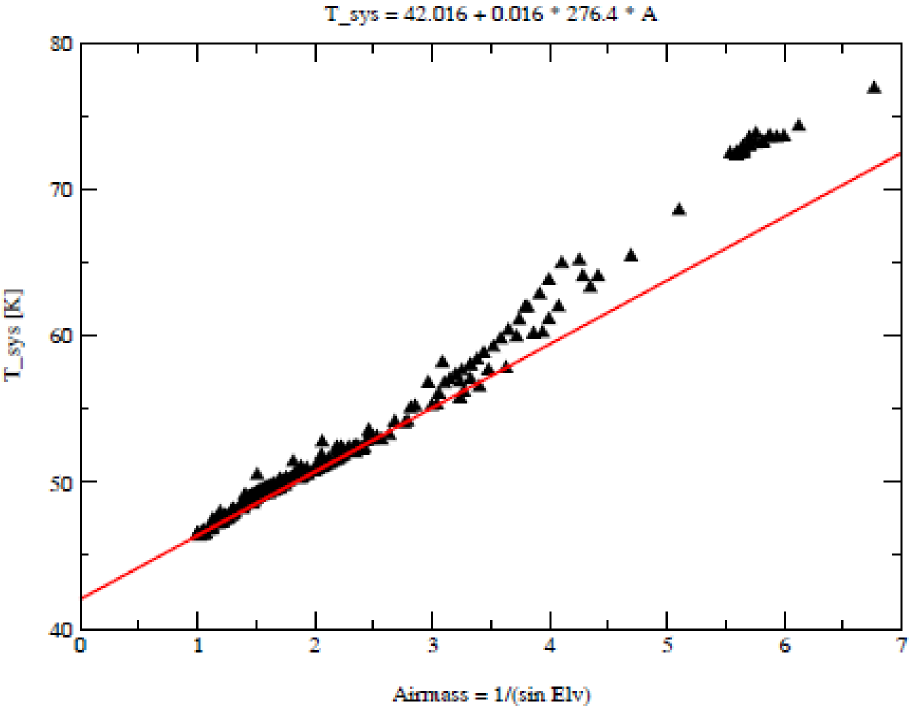
T_{ground} (spill over): usually a few K, depends on antenna and elevation.

T_{sky}: $$T_{sky} = \underbrace{T_{atm} \cdot (1 - \exp(-\tau/\sin(elv)))}_{\sim 20\text{-}200\text{K depending on } \tau} + \underbrace{T_{CMB} + T_{RB}}_{\text{a few K}}$$

τ is a function of frequency, water vapor, ...

Estimation of the opacity τ





$$T_{sys} = T_0 + T_{atm} \cdot (1 - \exp(-\tau / \sin(elv)))$$
$$T_{sys} \simeq T_0 + T_{atm} \cdot \tau \cdot \sin(elv)$$

Limiting noise

The limiting noise is given by: $\Delta T = \frac{T_{sys}}{\sqrt{\Delta \nu t}}$

Δν: bandwidth

t: integration time

→ if on source, the noise is increased

More bandwidth and longer integration times give a lower noise and, therefore, higher SNR:

$$SNR = \frac{T_{sys}}{\Delta T}$$

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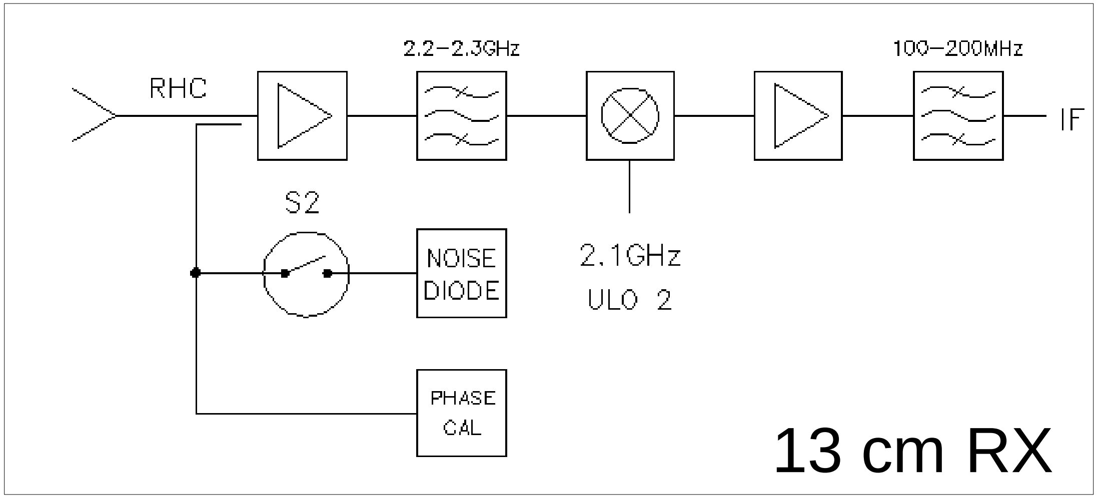
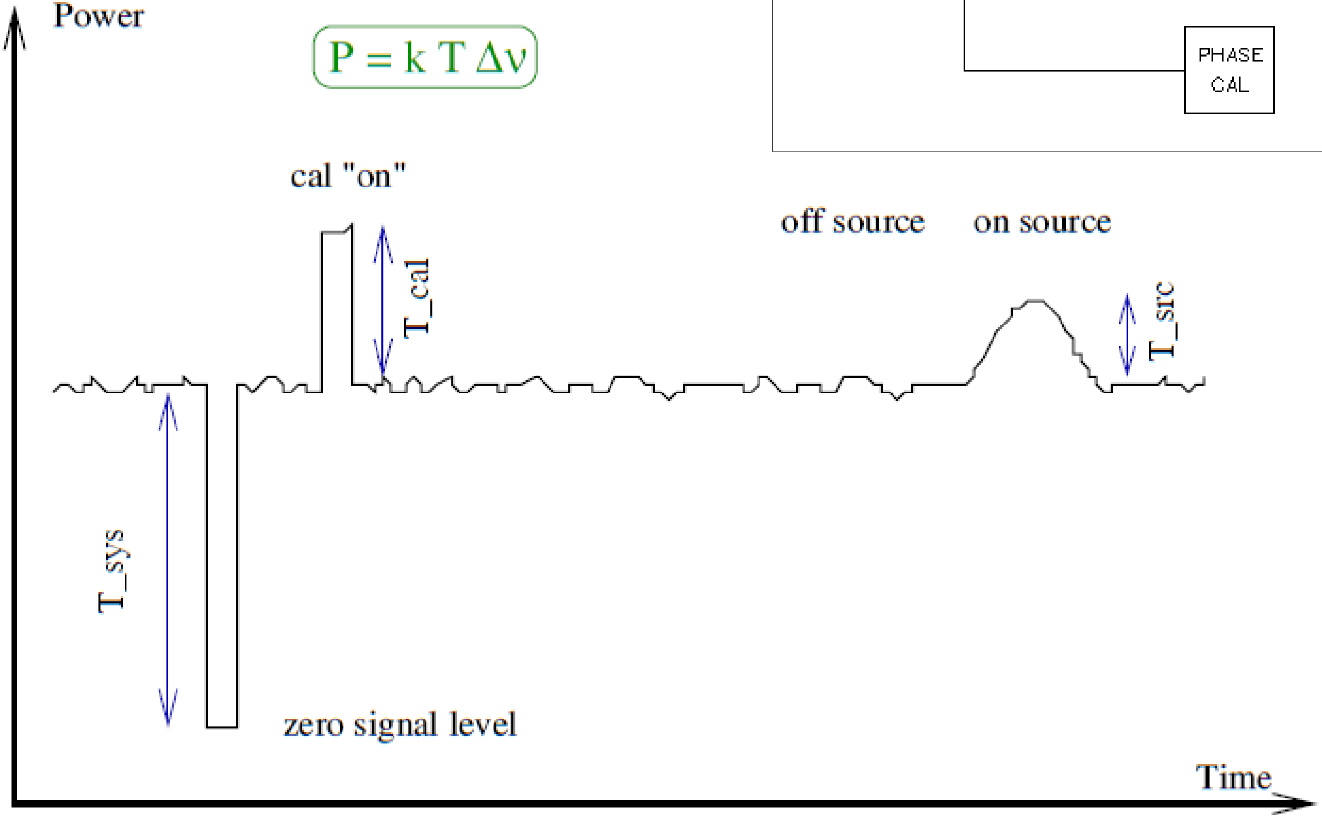
All measurements depend on the calibration temperature T_{cal}

Calibration temperature

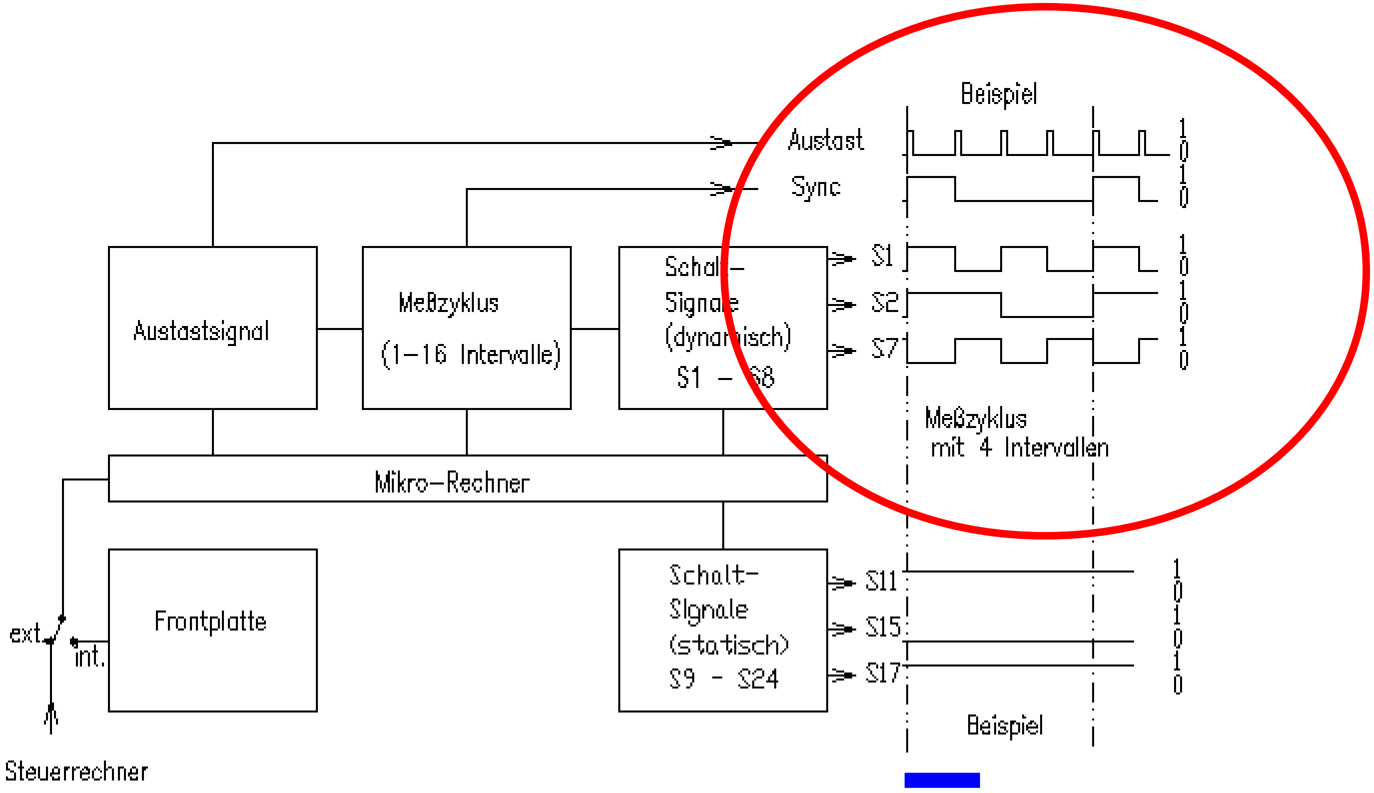




$$P = k\,T\,\Delta\nu$$

Calibration temperature II

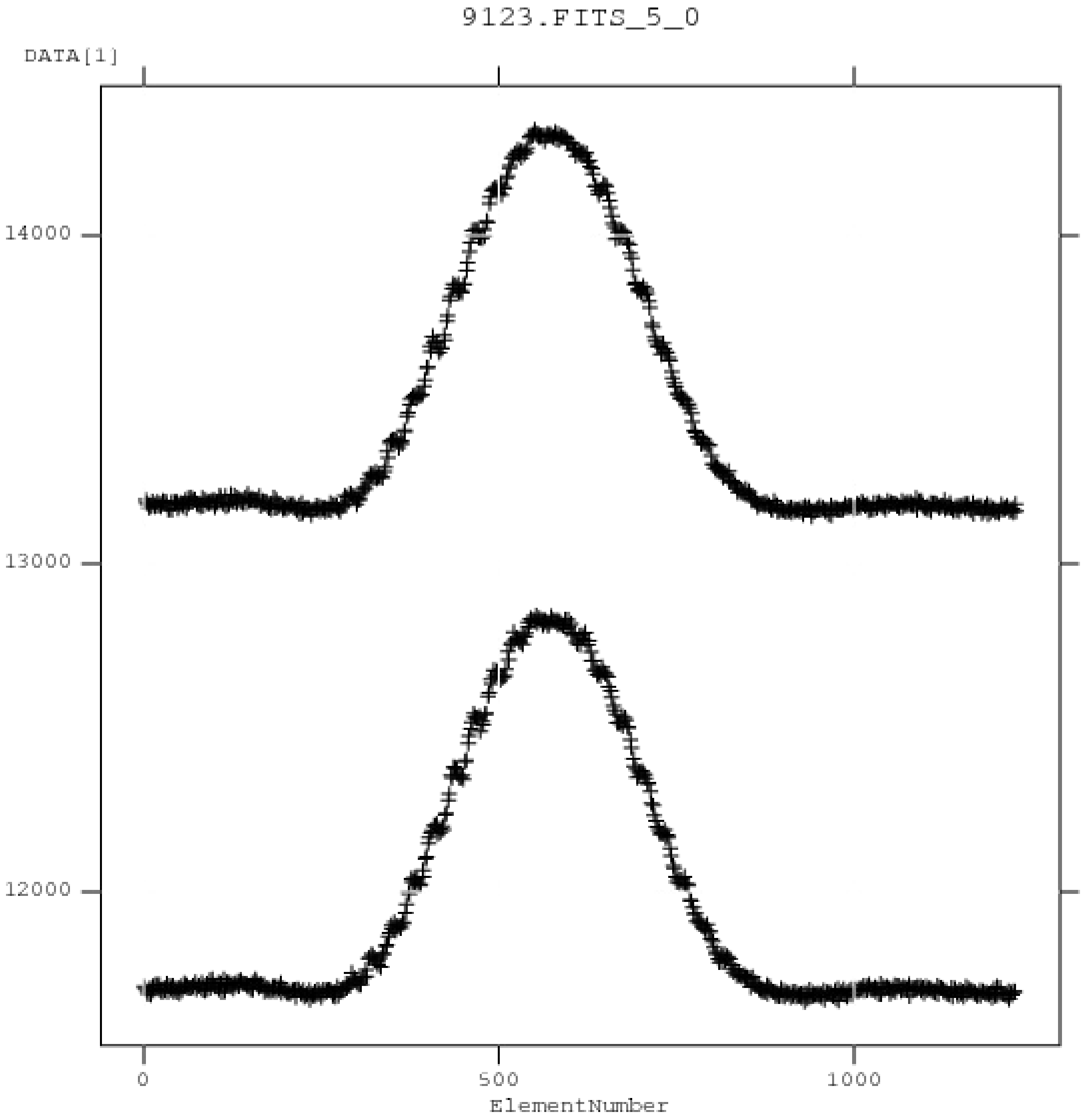
Calibration cycle for continuum observations:



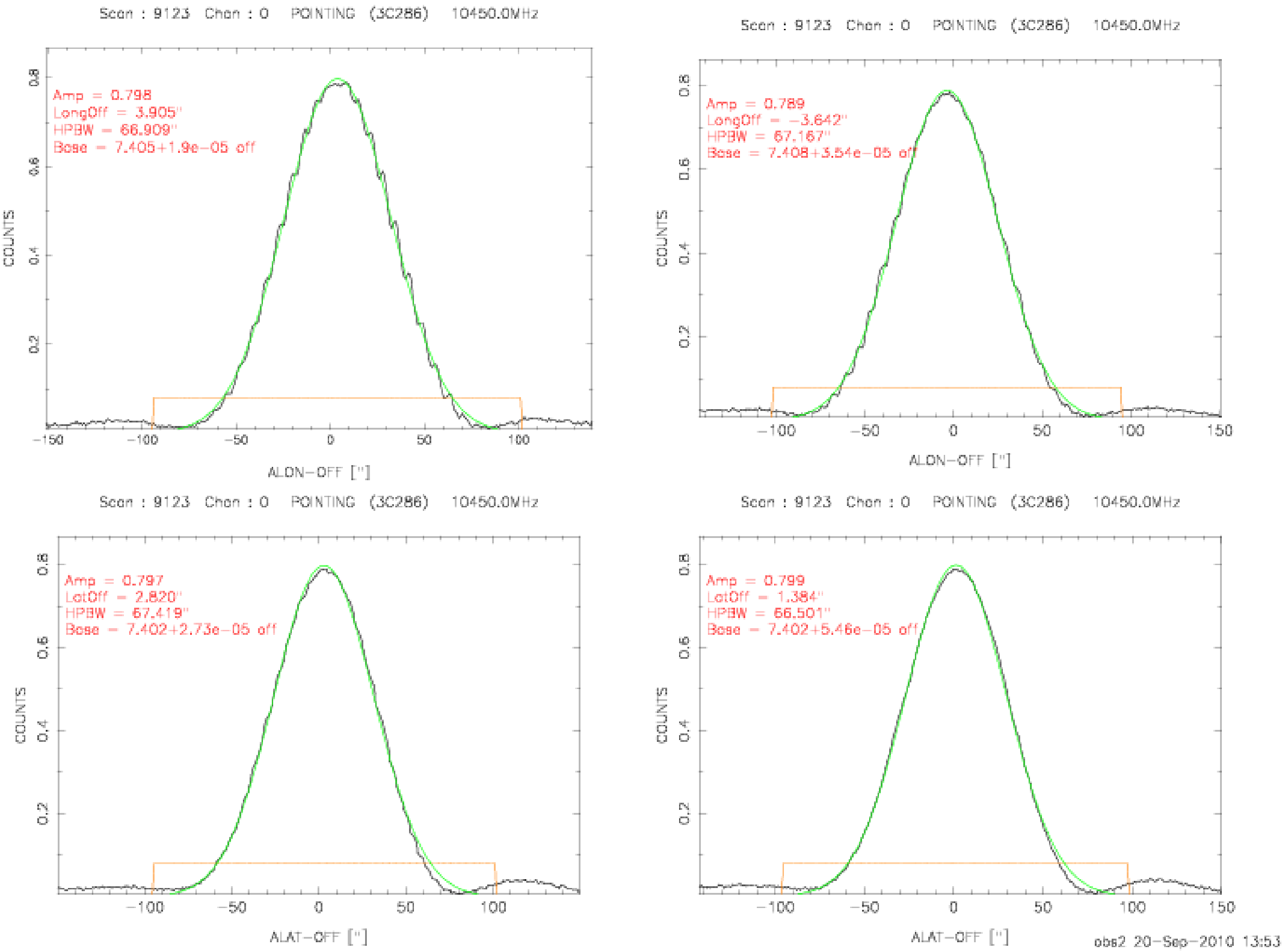
Single intervals of: 16ms

Measurement cycles of: 64ms

Cross scan (raw)



Cross scan (reduced)



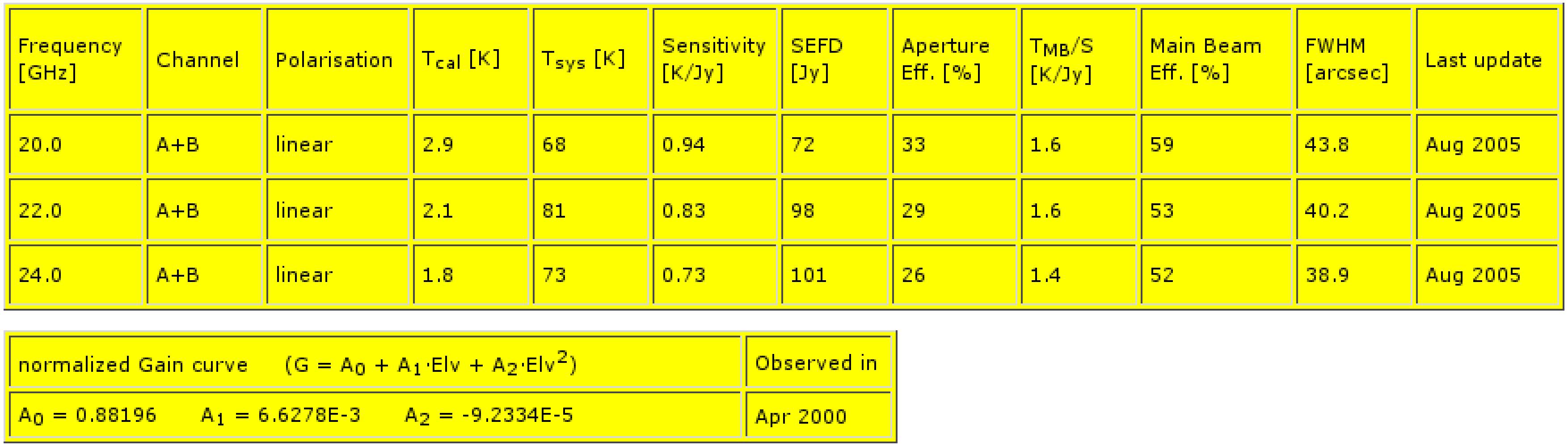
How does it actually work?

- Noise tube calibration:

$$T_{A[K]} = T_{cal[K]} \cdot T_{obs[counts]}$$

Information about T_{cal} is given on web page:

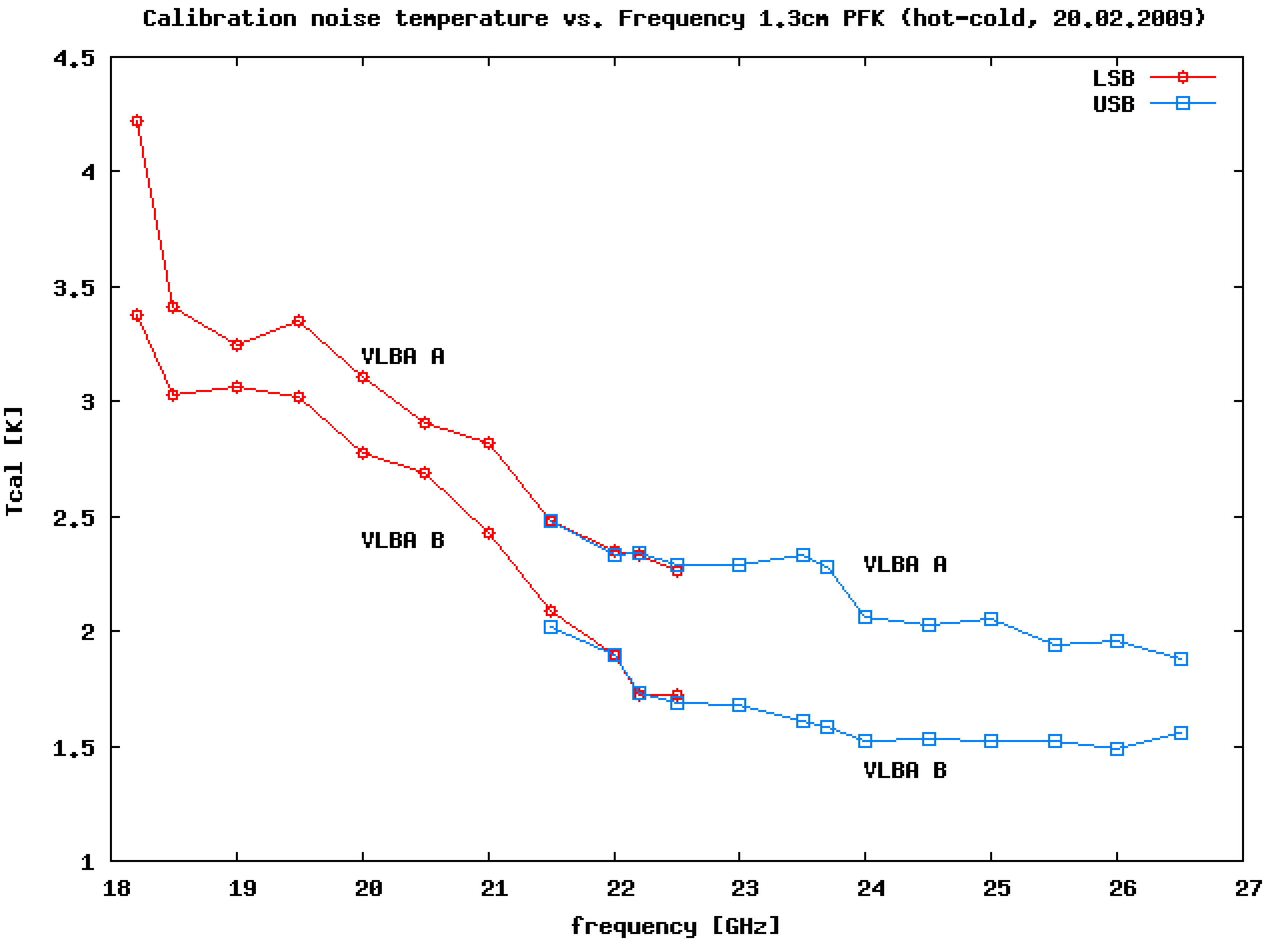
http://www.mpifr-bonn.mpg.de/div/effelsberg/receivers/receiver.html



Frequency [GHz]	Channel	Polarisation	T_{cal} [K]	T_{sys} [K]	Sensitivity [K/Jy]	SEFD [Jy]	Aperture Eff. [%]	T_{MB}/S [K/Jy]	Main Beam Eff. [%]	FWHM [arcsec]	Last update
20.0	A+B	linear	2.9	68	0.94	72	33	1.6	59	43.8	Aug 2005
22.0	A+B	linear	2.1	81	0.83	98	29	1.6	53	40.2	Aug 2005
24.0	A+B	linear	1.8	73	0.73	101	26	1.4	52	38.9	Aug 2005

normalized Gain curve ($G = A_0 + A_1 \cdot Elv + A_2 \cdot Elv^2$)	Observed in
$A_0 = 0.88196$ $A_1 = 6.6278E-3$ $A_2 = -9.2334E-5$	Apr 2000

Noise tube calibration



Calibration noise temperature vs. Frequency 1.3cm PFK (hot-cold, 20.02.2009)

Opacity correction

- Estimate τ from a number of measurements, sky-dip, or water vapor radio meter data
- Correct "backwards" the antenna temperature T_A:

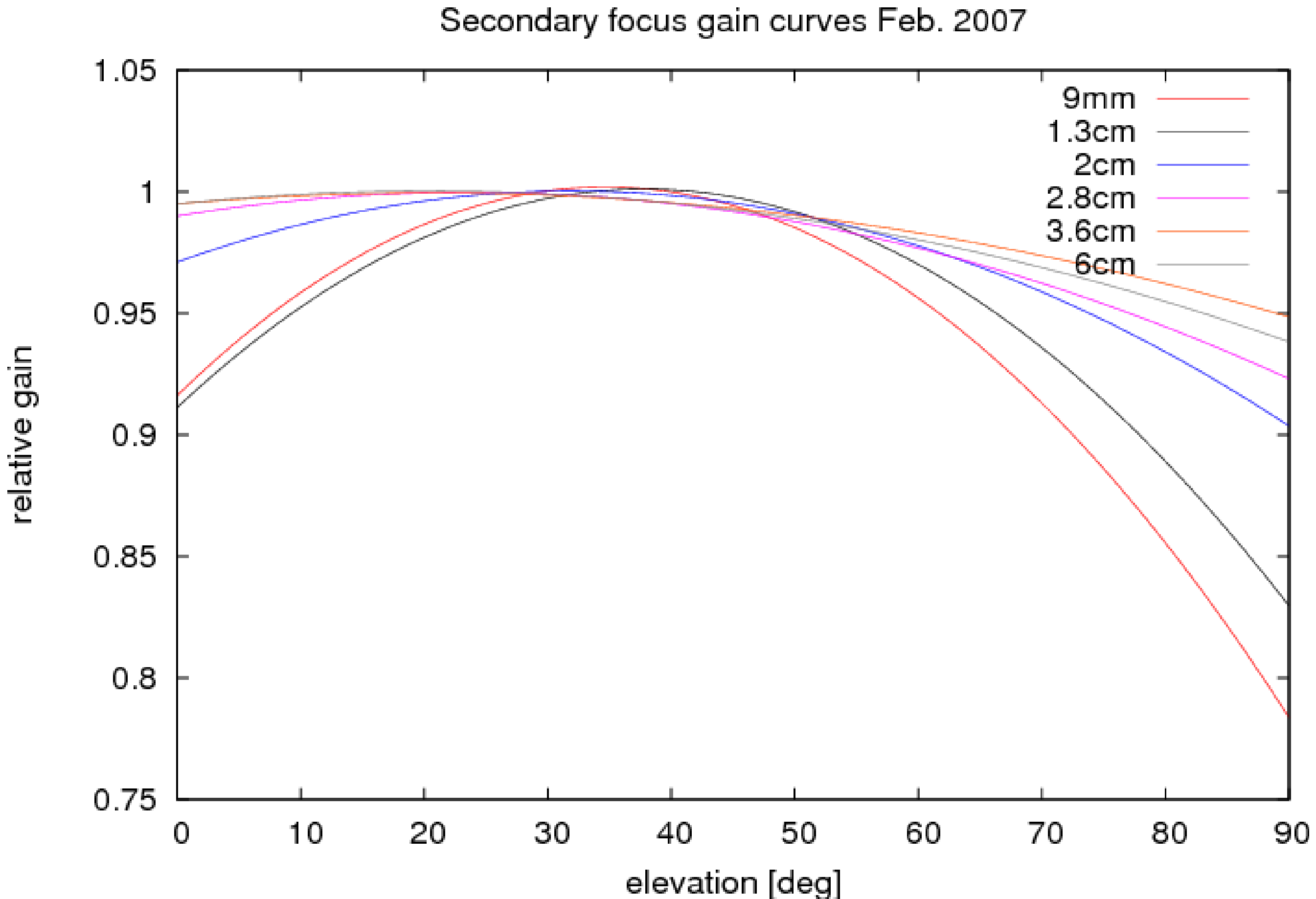
$$T'_A = T_A \cdot e^{\tau/\sin(elv)}$$

- Typical opacities observed at Effelsberg:

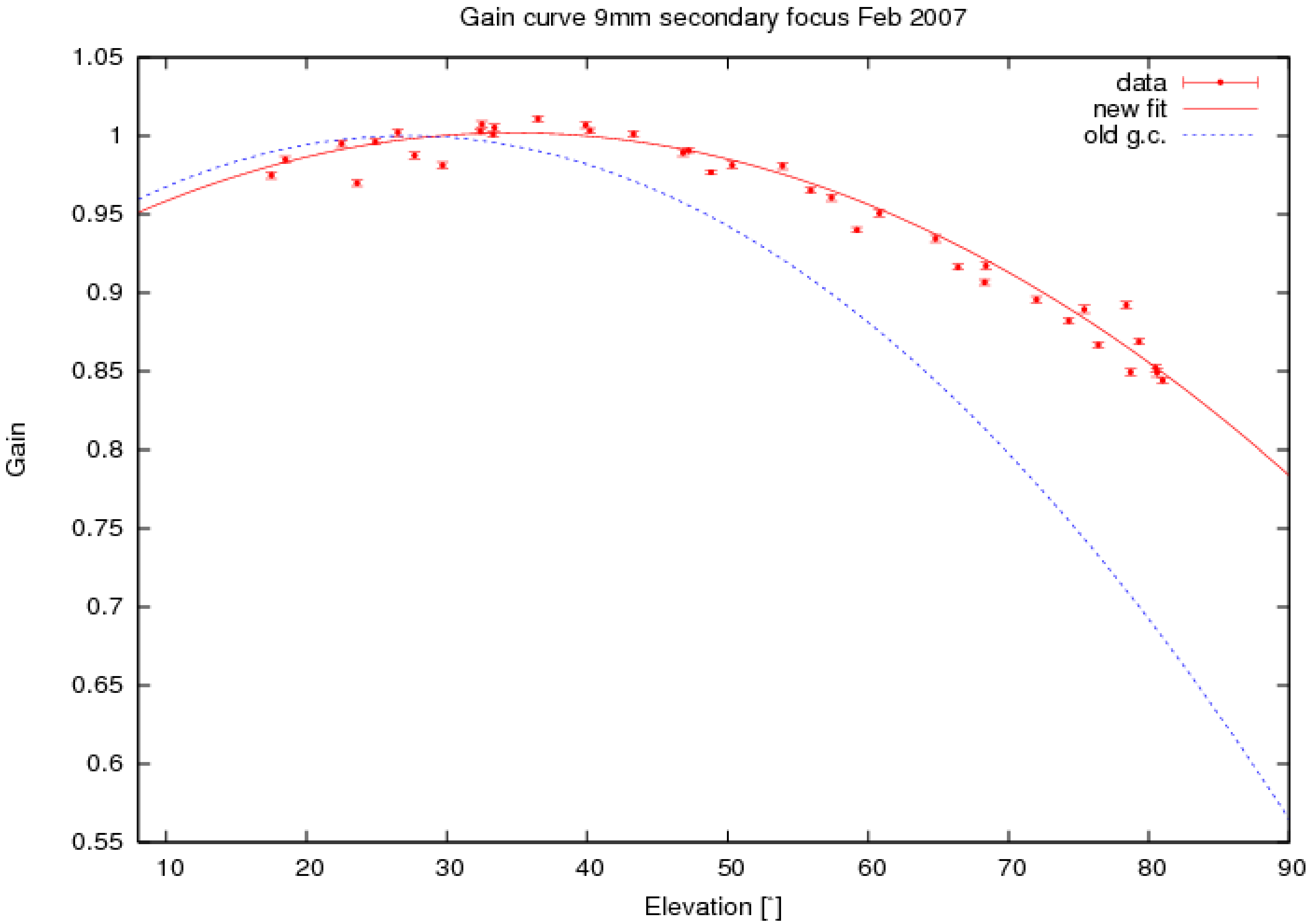
λ [cm]	τ
2	0.02-0.03
1.3	0.05-0.15
0.9	0.04-0.07
0.7	0.07-0.15
0.3	0.1-0.2

Gain elevation correction

- Surface of the Eb main dish is optimized to a parabola at 32º elevation.



Improvement by new sub-reflector



Gain elevation correction II

- Surface of the Eb main dish is optimized to a parabola at 32º elevation.
- Gain drops with high and lower elevations.
- Parameters of the gain curve G(elv) are given on the web page.

$$\boxed{T''_A = \frac{T'_A}{G(elv)} = \frac{T'_A}{A_0 + A_1 \cdot elv + A_2 \cdot elv^2}}$$

Final step: Kelvin to Jansky

- T_A and S are related by the sensitivity Γ.

$$\Gamma = \frac{\pi}{8 \cdot k} \eta_A D^2 = 2.844\text{E-}04 \, \eta_A \, D^2_{[m]} \quad [K/Jy]$$

$$\boxed{S[Jy] = \frac{T''_A[K]}{\Gamma[K/Jy]}}$$

- Since it is difficult to calculate η_A a priori, Γ is usually determined by observations of known calibrator sources (like 3C286, NGC7027, ...; see Baars et al. 1977)

Summary

- For a proper calibration of your data:
  - Check pointing (and focus) from time to time.
  - Observe regular a primary calibrator (non-variable, strong, and point-like), ideally over a larger range of elevations. Allows to check the given gain-curve, sensitivity, ...
  - Measure or calculate opacity.
  - Final calibrations includes:

$$\boxed{S = \frac{T_A \cdot e^{\tau / \sin(elv)}}{G(elv) \cdot \Gamma}}$$

Literature

- General reading:
  - J.D. Kraus: “Radio Astronomy”, 1986, Cygnus-Quasar-Books, Powel OH
  - K. Roholfs & T.L. Wilson: “Tools of Radio Astronomy”, 1996, Springer-Verlag, Berlin
  - J.W.M Baars: “The paraboloidal reflector antenna in radio astronomy and communication: theory and practice”, 2007, Springer, New York
- More special:
  - J.W.M Baars, et al., 1977, A&A 61, 99

Thanks you!