Pointing and single dish amplitude calibration

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- **Why?**

  Need accurate correlated flux densities for astronomy and the best SNR for geodesy.

- **What is needed?**

  Knowledge of system temperature T_{sys} and Sensitivity Γ

  or: **S**ystem **E**quivalent **F**lux **D**ensity

  in addition: good pointing and focus, "gain curve", ...

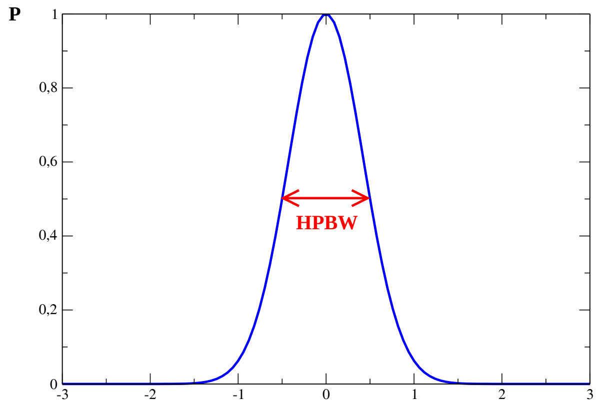
- And: gain information about antenna properties/performance

Measuring sources with a radio telescope

The main beam B of a radio telescope could be well described by a Gaussian with a **H**alf **P**ower **B**eam **W**idth θ_{HP}:

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

eg. at $\lambda = 6\,\mathrm{cm}$: Effelsberg 100m dish: $\theta_{\mathrm{HP}} \approx 150''$



The signal received is the convolution of the source structure with the antenna beam:

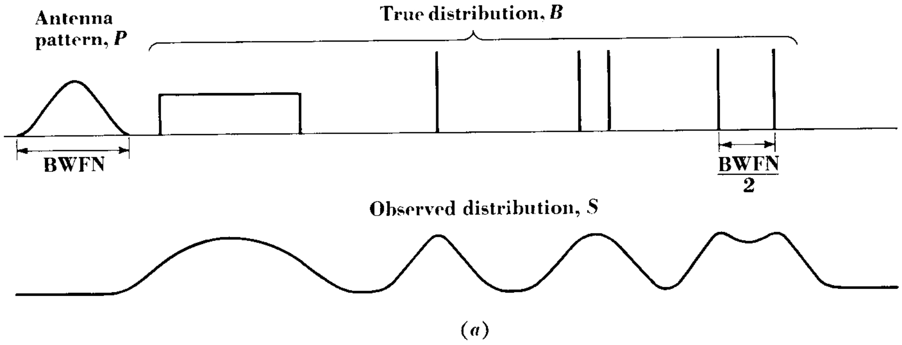


Fig. 6-11a. Smoothed distribution S observed with antenna pattern P.

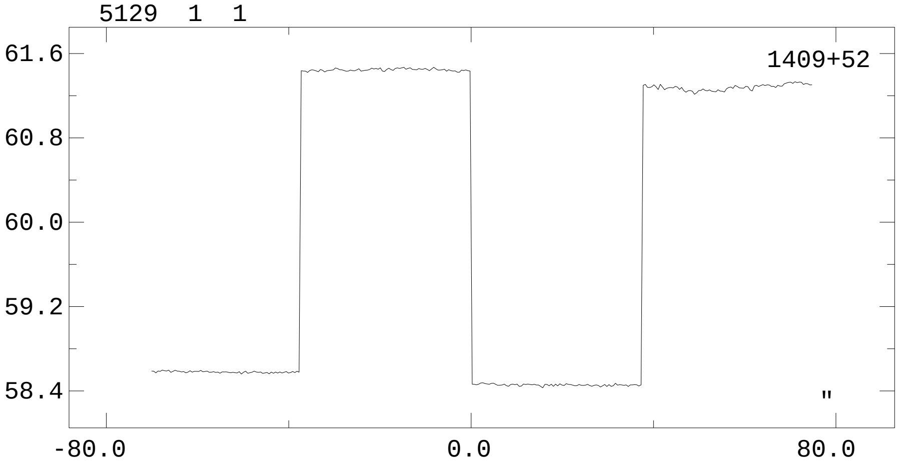
(J.D. Kraus: Radio Astronomy)

Assume that the sources are pointlike (good for calibration purposes).

How could we measure its strength?

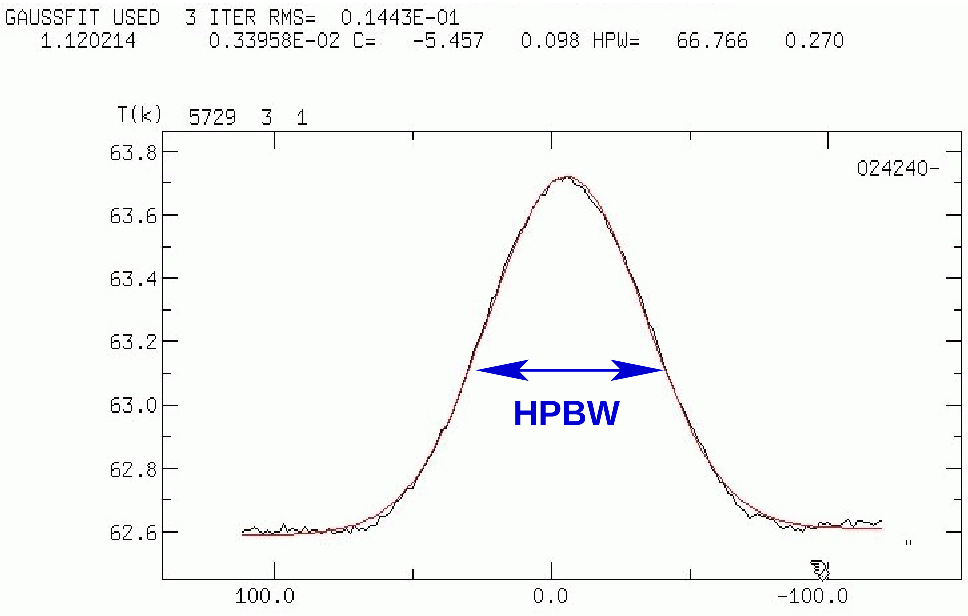
2 possibilities:

* On-Off:



← Time →

* Cross-Scan:



← Position →

Always measure on source and next to it!

Calibration theory

How does the received power correspond to the source flux density?

Flux density S $\quad \mathrm{S} = 1\,\mathrm{Jy} = 10^{-26}\mathrm{W\,m^{-2}\,Hz^{-1}}$

typical VLBI sources: 0.1–10 Jy

Power received by the antenna is a function of

- the flux density S,
- the collecting area A_{geom} (geometric aperture),
- the aperture efficiency η_A, and
- and the bandwidth $\Delta\nu$.

Define the effective aperture $A_{\mathrm{eff}} := \eta_A \cdot A_{\mathrm{geom}}$.

$$P = 0.5 \cdot S \cdot A_{\mathrm{eff}} \cdot \Delta\nu$$

factor 0.5 $\leftrightarrow$ feed responds only to one polarization

Temperature and power are equivalent:

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

Therefore, a radio source with flux density S has a corresponding antenna temperature

$$\begin{aligned} k \cdot T_{\text{src}} &= 0.5 \cdot S \cdot A_{\text{eff}} \\ \rightarrow T_{\text{src}} &= \frac{S\,A_{\text{eff}}}{2\,k} \end{aligned}$$

Define the **sensitivity** of an antenna:

$$\begin{aligned} \Gamma &= \frac{T_{\text{src}}}{S} \qquad (\text{“deg per Jansky”}) \\ \leftrightarrow \Gamma &:= \frac{A_{\text{eff}}}{2k} = \eta_A \frac{A_{\text{geom}}}{2k} = \eta_A \frac{\pi D^2}{8k} \end{aligned}$$

Aperture efficiency depends on surface accuracy σ, aperture blocking, ...:

$$\eta_A = f(\lambda, \sigma, ...) \qquad \text{(unknown a priori)}$$

	25m-dish	Effelsberg 100m-dish
$T_{\text{src}}/S = \Gamma =$	$\eta_A \cdot 0.18$ K/Jy	$\eta_A \cdot 2.84$ K/Jy

T_{src} corresponds to observed power from the source!

What do we receive from the receiver, the sky, ...?

What do we measure? The power we got from the receiver consists of various parts:

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

- T_{receiver}: ranges from a few to several tens of K (cooled receiver), much higher for uncooled ones.
- T_{ground} (spill-over): usually a few K, depends on antenna and elevation, could be quite high.
- $T_{\mathrm{sky}} = \underbrace{T_{atm} \cdot (1 - e^{-\tau/\sin \mathrm{Elv}})}_{\sim 20..200\,\mathrm{K}} + \underbrace{T_{CMB} + T_{RB}}_{\sim \mathrm{few\ K}}.$

  (τ depends on frequency, water vapor, ...)

The limiting noise is given by ($\Delta\nu$: bandwidth, t: integration time):

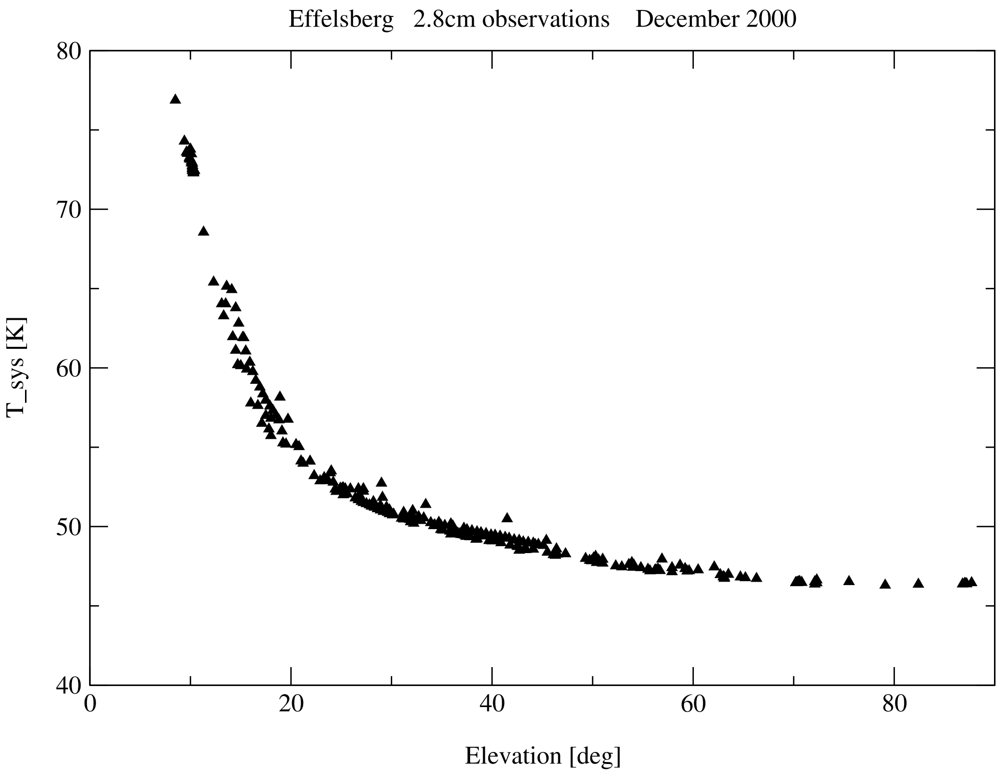
$$\Delta T = \frac{T_{\mathrm{sys}}}{\sqrt{\Delta\nu\, t}}$$

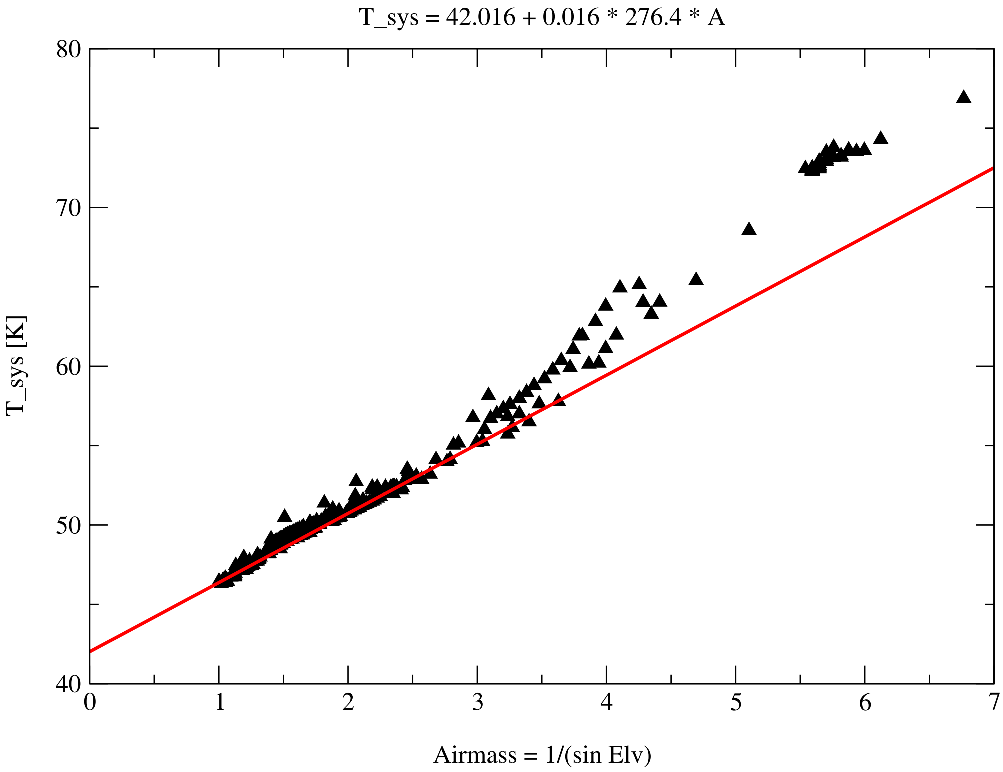
→ if on source, the noise is increased!

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

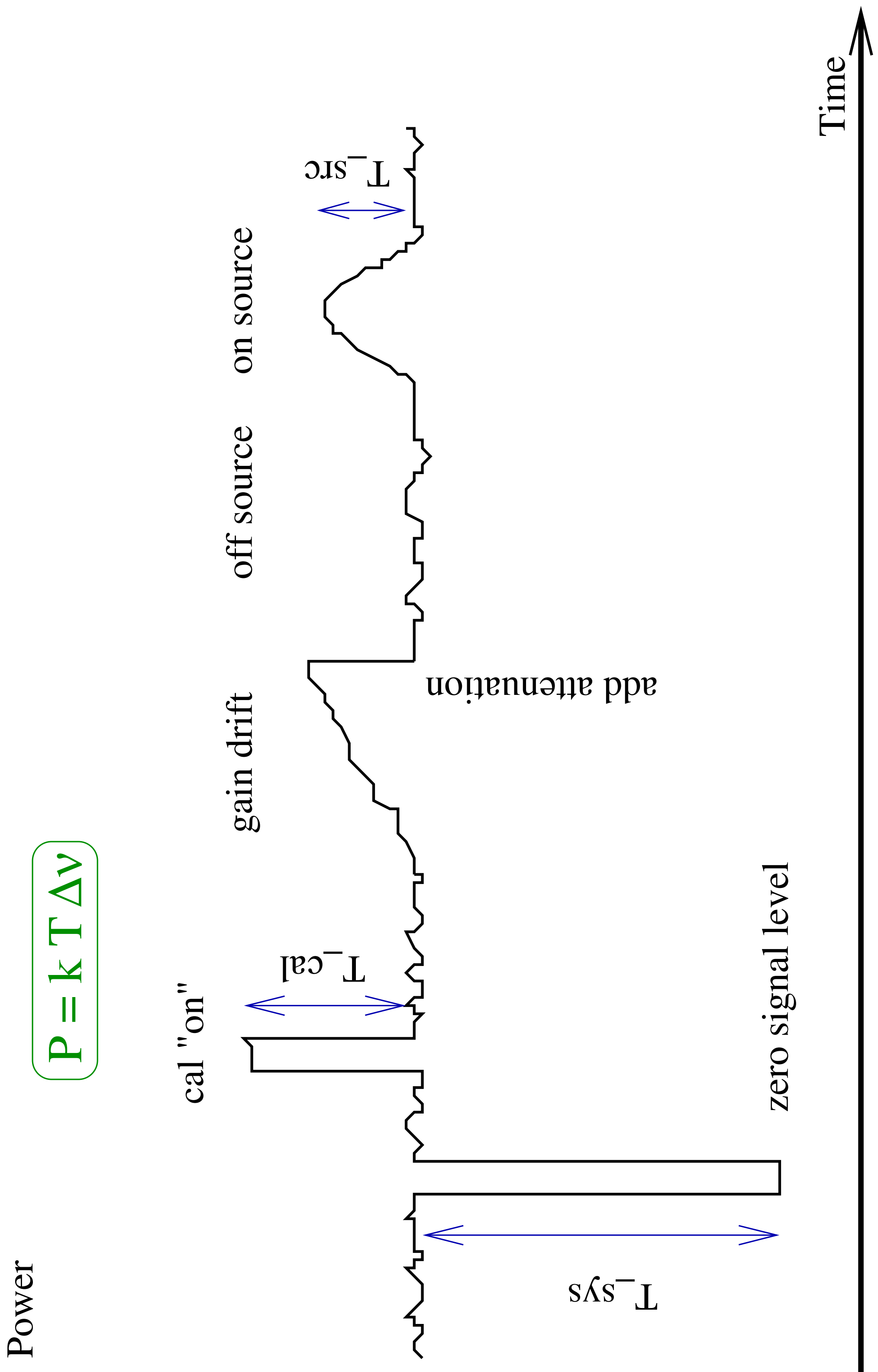
$$\mathrm{SNR} = \frac{T_{\mathrm{src}}}{\Delta T}$$

All measurements depend on the calibration temperature T_{cal}!





$$
\begin{aligned}
T_{\mathrm{sys}} &= T_0 + T_{atm} \cdot \left(1 - e^{-\tau/\sin \mathrm{Elv}}\right) \\
&\simeq T_0 + T_{atm} \cdot \tau \cdot \sin \mathrm{Elv}
\end{aligned}
$$



P = k T Δν
Power
Time
T_sys
zero signal level
cal "on"
T_cal
gain drift
add attenuation
off source
on source
T_src

How does the calibration actually work?

The interesting values are not known a priori: Γ, η_A, ...

Observe sources with known flux density S (eg. Baars et al. 1977), and compare with measured T_{src}

Good sources are:

- Strong
- Non-variable
- Point-like for the antenna used

System **E**quivalent **F**lux **D**ensity: $$\textbf{SEFD} = \frac{T_{\text{sys}}}{\Gamma} = \frac{T_{\text{sys}}}{T_{\text{src}}/S}$$

(independent of the actual value of T_{cal}!)

Measure the power ratio Y while on-source and off-source

$$Y = \frac{T_{\text{src}} + T_{\text{sys}}}{T_{\text{sys}}}$$

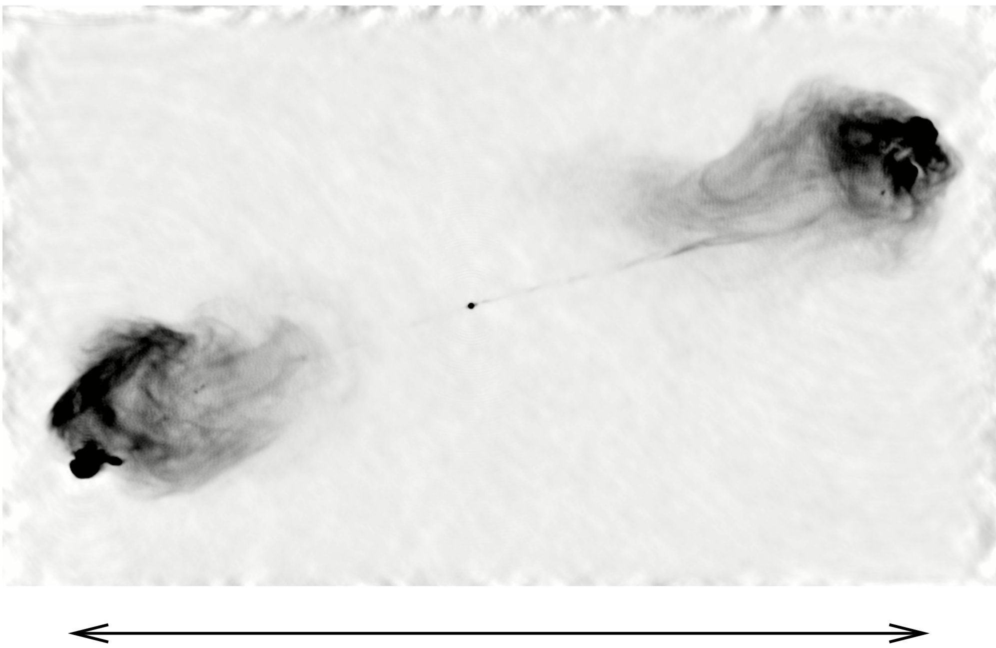
$$= \frac{S + \textbf{SEFD}}{\textbf{SEFD}}$$

$$\Rightarrow \textbf{SEFD} = \frac{S}{Y - 1}$$

The stronger a source is, the better, but:

- Strong sources might be extended, eg. Sun, Moon, Cyg A, Cas A, ...
  If a source is resolved, the apparent (ie. the peak) flux density is less than the total.
- power detector should be used in linear regime!

Cyg A – VLA 6cm Perley et al. 1984 (ApJ 285, 35)



Beamsizes at $\lambda = 3.6\,\mathrm{cm}$:	
D = 10 m	14.9 arcmin
D = 25 m	5.9 arcmin
D = 100 m	1.5 arcmin

Good sources for all antennas:

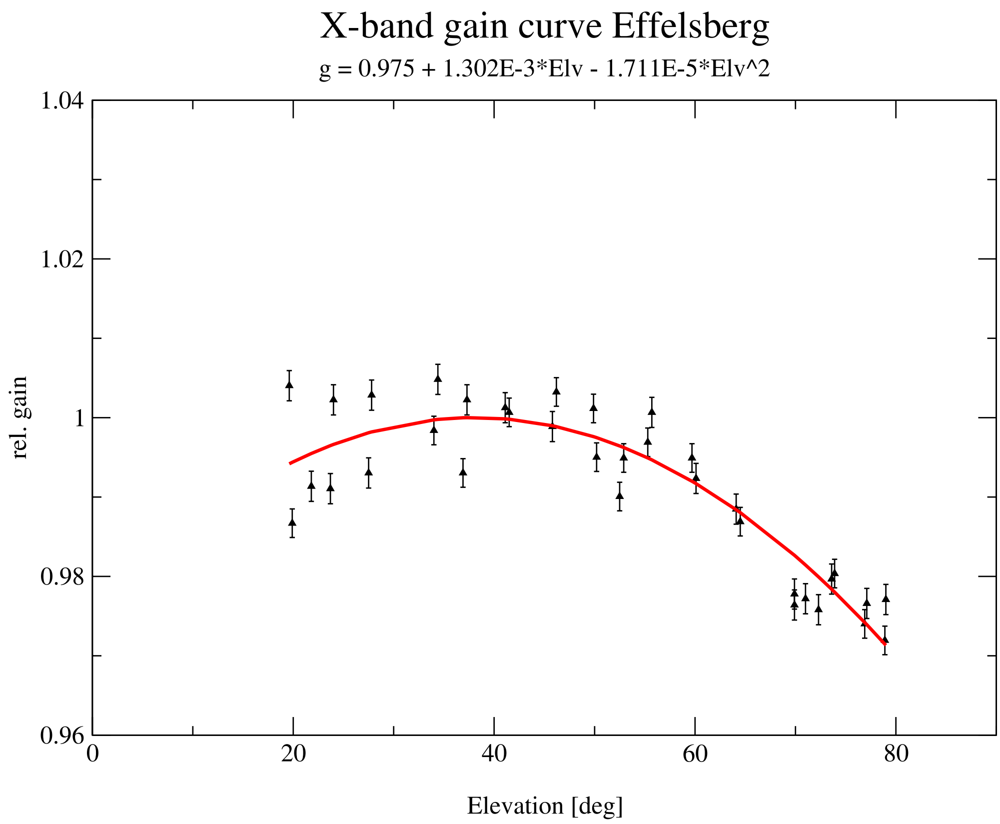
3C123, 0521−365, 3C147, 3C161, 3C286, 3C295, 3C380

For small antennas only: Tau A, Ori A, Vir A, Cyg A, Cas A

There are lots of strong sources which are suitable for pointing the antenna, but which vary in time, e.g. 3C84, 3C273, ...

For most antennas the aperture efficiency varies with elevation. This could usually be described by a parabola.

Measure it by observing a source from the horizon to high elevations.



In addition:

- At high frequencies (ie. $\geq$ 15 GHz) atmospheric absorption must be considered: $S_{obs} = S_{true} \cdot \exp(-\tau / \sin \mathrm{Elv})$.
- Generally, weather effects become more serious are short wavelength (time variable gain).
- The calibration temperature T_{cal} should be well known.

  Beware: It could vary over the band.
- At some bands, interference (RFI) might be an additional problem.

Possible sources of errors are:

- T_{cal} not well known (variations over time and/or frequency).
- Receiver not in the linear regime, or

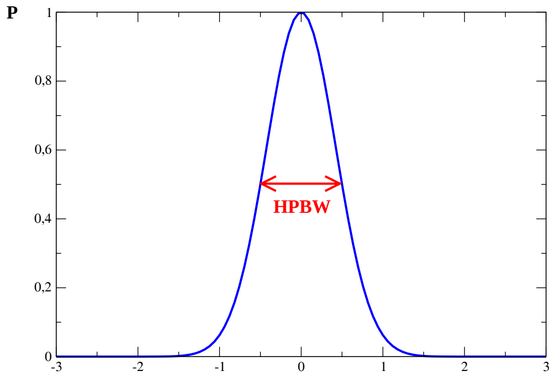
  VCs close to (or in) saturation
- zero level not taken into consideration
- bad pointing, bad focus

Pointing

Remember: the telescope beam is described by a Gaussian:

$$B = \exp\left[-4\ln 2\left(\frac{\theta}{\theta_{\mathrm{HP}}}\right)^2\right]$$

$$\theta_{\mathrm{HP}} \approx 1.2 \cdot \lambda / D$$



bad pointing ⇒ loss of signal strength!

$$\Delta\theta = \begin{array}{l} 0.1\,\theta_{\mathrm{HP}} \rightarrow B = 0.97 \\ 0.2\,\theta_{\mathrm{HP}} \rightarrow B = 0.90 \\ 0.3\,\theta_{\mathrm{HP}} \rightarrow B = 0.78 \end{array}$$

Pointing accuracy $\lesssim 0.1\,\theta_{\mathrm{HP}}$ is needed (all over the sky).

But: Telescope pointing depends on azimuth and elevation!

Reason: instrumental effects (eg. instrumental zenith differs from real one)

Pointing model (cf. FS Manual Volume 2) is needed: Derivation by observation of strong, point-like sources all over the sky.

Best done with Cross-Scans (FS: five-points): Scan across source in azimuth and elevation, fit Gaussian, correct offset.

Repeated pointing checks could be important!!

Focus

Received power varies with distance (of feed or subreflector) of the dish. The variation is approximately Gaussian.

Focus should be correct to a fraction of wavelength!

Check (and correct) focus by measuring the power at different distances. Look for comparable levels on both sides. If distance is not too large, fit Parabola.

Look for spill-over (ground radiation). When *off source*, check whether power changes when focus moves.

If this is the case, do focus "manually". Try different settings and look for comparable levels on both sides, use mean.

If possible, don't change the focus during a geodetic experiment.

Use the FS

The Field System allows:

* to perform pointing checks and determine the pointing model

using `aquir`, `fivept`, etc. and `pdplt` for the analysis.

Automated pointing models using the FS (by Ed Himwich)

* to perform calibration measurements

using `onoff` and `gnplt` for the analysis.

Antenna gain calibration (by Carl Holmstrom)

Literature

General reading:

- J.D. Kraus: "Radio Astronomy", 1986, Cygnus-Quasar Books, Powell OH
- K. Rohlfs & T.L. Wilson: "Tools of Radio Astronomy", 1996, Springer-Verlag, Berlin, Heidelberg
- G.B. Taylor, C.L. Carilli, & R.A. Perley (eds.): "Synthesis imaging in Radio Astronomy II", 1999, ASP conference series vol. 180
- A.R. Thompson, J.M. Moran, & G.W. Swenson: "Interferometry and Synthesis in Radio Astronomy", 1986, John Wiley & Sons, New York

More special:

- J.W.M. Baars, R. Genzel, I.I.K. Pauliny-Toth, & A. Witzel, 1977, A&A **61**, 99
- J. Conway, "EVN Calibration", 1997, EVN report No. 2
- M. Ott, A. Witzel, A. Quirrenbach, et al., 1994, A&A **284**, 331

and certainly:

- The Field System Manual, Vol. 1 & 2.