Calibration of the Effelsberg 100m telescope

A. Kraus — MPIfR
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This document **shortly** describes how to get from source counts to Jansky. For more detailed information see the various textbooks available. Note, that there are various pieces of software which could be used to do the necessary corrections. However, the strategy of calibration is the same for all observing methods.

1 Noise tube calibration

To convert the measured signal from counts into temperatures (ie. system temperature $T_{\rm sys}$, antenna temperature $T_{\rm A}$), it is necessary to know the value of the noise diode in K. This information is available in the WWW, the receiver information folders in the control room in Effelsberg or the systems group (K. Grypstra et al.).

The software (ie. TOOLBOX or CLASS) is designed in a way, that usually it is sufficient to multiply the given value of $T_{\rm cal}$ to the data to get temperatures instead of counts:

$$T_{A\,[\rm K]} = T_{\rm cal\,[K]} \cdot T_{\rm obs\,[counts]} \quad . \tag{1}$$

Note, that the $T_{\rm cal}$ might vary with frequency and could be different between LCP and RCP.

2 Opacity correction

The atmosphere leads to an attenuation of the observed signal (significant at least for observations at $\nu \gtrsim 15\,\rm GHz$) by a factor $e^{-\tau \cdot AM}$; τ is the zenith opacity (which depends on the frequency) and $AM = 1/\sin(\rm Elv)$ the "airmass". Hence, the following correction has to be applied to the data:

$$T_A^* := T_A \cdot e^{\tau \cdot AM} \tag{2}$$

To derive the actual opacity at a given time, the following relation could be used:

$$\begin{aligned} T_{\rm sys} &= T_0 + T_{\rm Atm} \cdot \left(1 - e^{-\tau \cdot AM}\right) \\ &\simeq T_0 + T_{\rm Atm} \cdot \tau \cdot AM \quad . \end{aligned} \tag{3}$$

Be sure to have the correct value of $T_{\rm cal}$ applied to the data! If not, $T_{\rm sys}$ and also τ will be wrong by a factor $T_{\rm cal}$.

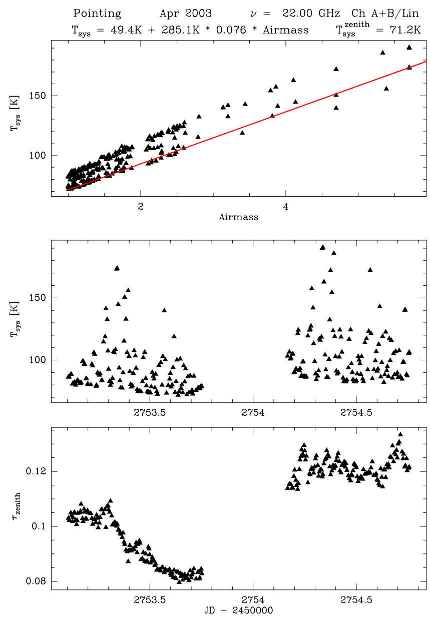
The system temperature is known (or easily determined) for each individual observation, as well as the air mass. The atmospheric temperature could be assumed to be equal the air temperature (on ground level) or – better – calculated by the following approximation:

$$T_{\mathrm{Atm}} = 1.12 \cdot T_{\mathrm{ground}} - 50\,\mathrm{K} \simeq T_{\mathrm{ground}} - 17\,\mathrm{K} \quad . \tag{4}$$

With a number of measurements, T_0 and also τ could be derived by a least-square-fit. As the opacity is strongly dependent on the weather, it might be a good idea to use a "two-step-procedure" to calculate a list of opacities against time. First, fit a "lower envelope" to the whole data set, to determine the lowest opacity τ_{min} and especially T_0. In a second step for each individual measurement the opacity could be determined by using the measured T_{sys}, the AM, T_{Atm}, and T_0:

$$\tau = -\frac{1}{\mathrm{AM}} \cdot \ln\left(1 - \frac{T_{\mathrm{sys}} - T_0}{T_{\mathrm{Atm}}}\right) \quad . \tag{5}$$

This could be seen in the figure: In the upper panel the fit to determine T_0 is given, in the lower panel τ against time is plotted (the middle panel gives system temperature against time).



Typical opacities measured at the Effelsberg site are presented in the following table.

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

Table 1: Typical zenith opacities at Effelsberg. Note, that τ depends on the weather conditions; especially at high frequencies!

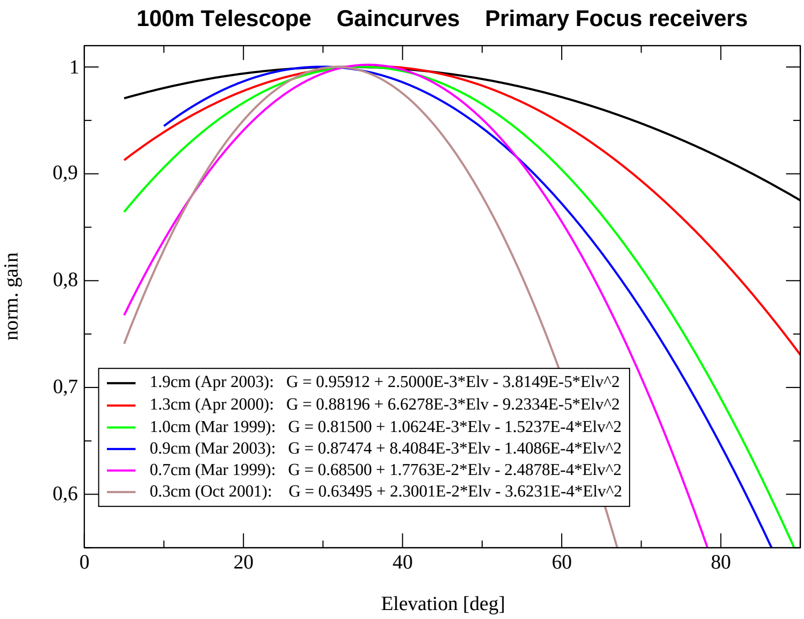
The recently installed Water-Vapour Radiometer (www.mpifr-bonn.mpg.de/staff/aroy/wvr.html) measures the opacity instantly (at $\lambda = 1.3\,\mathrm{cm}$). Note, that there is no hot/cold-calibration in Effelsberg (like eg. at the 30m telescope).

3 Gain-elevation correction

The surface of the main dish is adjusted by holography measurements using a geo-stationary satellite at an elvation of 32°. When moving to higher or lower elevations, the dish always keeps a parabolic form (due to the principle of homology) and therefore has one well-defined focal point. But, small-scale deformations of the surface (and the panels itself) lead to a loss of sensitivity. That could usually described by a parabola in elevation[1]; hence the following correction has to be applied during data analysis:

$$T_A^{**} := \frac{T_A^*}{G(\mathrm{Elv})} = \frac{T_A^*}{A_0 + A_1 \cdot \mathrm{Elv} + A_2 \cdot \mathrm{Elv}^2} \qquad (6)$$

G should be normalised to one. The elevation-dependence gets stronger with decreasing wavelength; examples are shown in the following figure.



4 Final calibration (K-to-Jy conversion)

To get Janksy from antenna temperature one has to know the sensitivity Γ ("Kelvin per Jansky") of the telescope (for the the observing frequency).

Theoretically, Γ is given by the antenna diameter D and the aperture efficiency[2] η_A:

$$\Gamma = \frac{\pi}{8k}\eta_A D^2 = 2.844 \cdot 10^{-4}\,\eta_A D^2_{[\mathrm{m}]} \overset{\mathrm{Effelsb.}}{=} \eta_A \cdot 2.844\,\mathrm{K/Jy} \quad . \qquad (7)$$

[1] Sometimes a polynomial of higher order has to be used.

[2] which is actually a product of several efficiencies describing the loss of power due to eg. the surface inaccuracies η_{surf}, aperture blocking η_{bl}, tapering η_{tap}, etc.: $\eta_A = \eta_{\mathrm{surf}} \cdot \eta_{\mathrm{bl}} \cdot \ldots$.

However, it is difficult to calculate η_A a priori. Therefore, usually, Γ is determined through observations of known calibrator sources (like 3C286, NGC7027,...). Note, that due to eg. focus changes (due to weather effects), the sensitivity could be mildly time dependent. Additionally, variations in the strength of the noise calibration as well as pointing errors could lead to apparent variations in the sensitivity. All these effects should be "monitored" by observing the prime calibrators frequently.

So finally, we have

$$S_{[\mathrm{Jy}]} = \frac{T_A^{**}{}_{[\mathrm{K}]}}{\Gamma_{[\mathrm{K/Jy}]}} \quad . \tag{8}$$

If the observed sources is not point-like, but somewhat extended (compared to the width of the main beam), a correction factor C_s has to be applied to avoid underestimation of the real flux density (for a pointlike source $C_s = 1$).

In summary, the calibration procedure could be described by

$$S_{[\mathrm{Jy}]} = \frac{T_{A[\mathrm{K}]} \cdot e^{\tau AM} \cdot C_s}{G \cdot \Gamma_{[\mathrm{K/Jy}]}} \quad . \tag{9}$$

5 Main beam brightness temperature

The conversion from antenna temperature into main beam brightness temperature and flux density could be done using the *main beam efficiency*

$$\eta_{MB} = \frac{T_A}{T_{MB}} = \frac{\Omega_{MB}}{\Omega_A} \tag{10}$$

with the solid angles of the main beam Ω_{MB} and the full beam Ω_A. To determine T_{MB} and (with T_A) η_{MB} one could observe a (pointlike) calibrator (with known flux density S), and use the *Rayleigh-Jeans-law*:

$$S = \frac{2\,k\,T_{\mathrm{MB}}\,\Omega_{MB}}{\lambda^2} \quad . \tag{11}$$

For Gaussian source and beam shapes this simplifies to

$$S = 2.65 \frac{T_{\mathrm{MB}\,[\mathrm{K}]}\theta_{0\,[\mathrm{arcsec}]}}{\lambda^2_{[\mathrm{cm}]}} \tag{12}$$

using the relation $\Omega \simeq 1.133\theta_{MB}^2$ and assuming that $\theta_{src} = \theta_{MB} = \theta_0$.

Note, that for a source which has a size much larger than the beam size, T_{MB} is equal the real brightness temperature of the source and therefore – in contrast to T_A – independent of the telescope used!