Appendix E: Determination of System Temperature (updated 13 jan 09)

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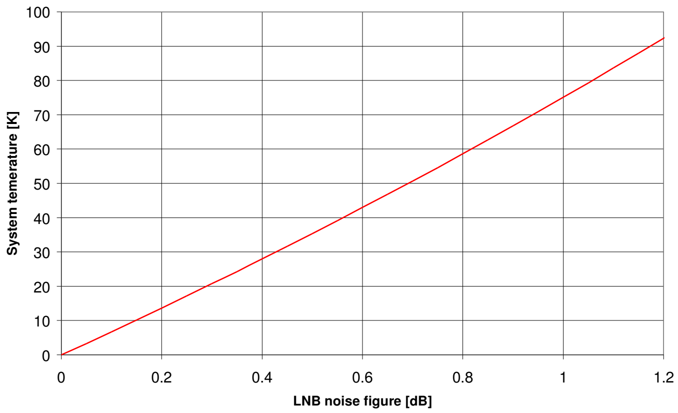
Value from the LNB noise figure:

The LNB's noise figure NF = 0.3 dB gives a system temperature

$$T_{sys} = T_{amb}(10^{(NF/10)} - 1) \;=\; 21 \text{ K}$$

if we use an ambient temperature of 290 K. The relation is shown in the figure below:



But this is the noise temperature of the LNB only. The true system temperature includes a number of other factors

- Any absorption by the plastic cover of the LNB
- Illumination losses, due to the fact that the horn antenna of the LNB illuminates the parabolic dish only partially and unevenly
- Spill-over losses: some fraction of the LNB's antenna pattern reaches beyond the rim of the parabolic dish. Hence, some ground radiation will enter
- If the dish is not of solid metal, but made of wire-mesh, there could be 'feed-through' losses, as there is partial pick-up of thermal radiation from the ground behind the dish

Our measurements give about 170 K. This corresponds to a total of 1.7 dB of spill-over and illumination losses.

Measurement of the overall system temperature:

The basic technique is to observe a source of known temperature (‘hot source’ or ‘onsource’) and compare it with the empty sky (viz. a cold source of known temperature- ‘cold source’ or ‘off source’). The ratio of the received powers is

$$Y = P_{ON}/P_{OFF} = (T_{SYS} + T_{HOT}) / (T_{SYS} + T_{COLD})$$

where T_{HOT} and T_{COLD} are the corresponding source temperatures, and we measure the power ratio Y. This gives the system temperature as

$$T_{SYS} = (T_{HOT} - Y\,T_{COLD}) / (Y-1)$$

We may apply this to any of these possibilities

Hot source	T_{SOURCE}	Filling factor*	T_{HOT}	Cold source	T_{COLD}
Calibrator	290	1	290	Sky background	3
Sun	11000	0.09	1000	Sky background	3
Moon	200	0.09	18	Sky background	3

When using the Sun or the Moon, we have to correct for the filling factors for these bodies, as they do not fill completely the antenna beam (* in the above table, we show the values for the repaired ESA-Dresden dish). Fortunately, this correction does not change significantly with the season or the lunar phase, and the temperature variations of these bodies are also quite small for our purposes. For instance, the lunar surface temperature varies by only ±20 K during the lunar cycle. For more accurate analyses using the Sun, one may use the solar fluxes measured daily by e.g. Penticton or Learmonth observatories.

In our analyses we had assumed a sky temperature of 3 K, whereas it would have been more accurate to include the thermal emission of the atmosphere – which would give about 5 K. Furthermore, we should have taken the trouble to separate the sky background from the receiver background by performing sky measurements at a number of elevations. Finally, we did not take notice whether the sky was cloudless or was overcast. These issues do not change the values strongly, and they would be addressed if need might arise in the future for a more accurate determinations of the system temperature. The true value of the background is not a parameter of great importance for our context: For instance, if one measured with our calibrator source an ON/OFF increase of 4 dB, the derived system temperature would vary on the assumed background temperature as:

Background [K]	0	3	5	10
T_{SYS} [K]	192	186	183	175

Value from Flux Calibration with Ground Observation:

Using the thermal emission by the Holiday Inn building, we derive by assuming an ambient temperature of 290 K:

Instrument	Date	calibration [dBµV]	background [dBµV]	T_system
ESA	24 june 07	45	40.8	175
ESA	22 june 07	45.3	40.65	175
ESA	20 june 07	44.8	40.3	155
ESA	4 june 07	44	40	186
ESA	30 apr 07	45.9	41.6	166
ESA	30 apr 07	46.2	41.8	160
ESA	26 apr 07	46.5	42	155
ESA	26 apr 07	45.9	41.6	166
ESA	26 apr 07	46.7	42.1	150
ESA	24 apr 07	46.18	42.3	196
small dish	30 apr 07	65.3	62.3	285
small dish	24 apr 07	65.4	62.367	285
ESA pre-repair	27 feb 07	44.4	41.8	350
ESA pre-repair	14 feb 07	46.67	43.02	216

One notes that the defocused ESA-Dresden dish had a substantially higher system temperature than the telescope after its repair. The Small Dish has a similar high system temperature – both instruments also have about the same HPBW.

Antenna temperatures of Sun and Moon:

Likewise, one can use the measured antenna temperatures and the signal levels on and off-source to derive the system temperature. But as the antenna temperatures are based on the flux calibration with the Holiday Inn, these values are not independent, but only serve as an overall consistency check.

Instrument	ESA pre-repair	ESA	ESA	Small Dish
Date	14 feb 07	26 apr 07	24 jun 07	30 apr 07
Target	Sun	Sun	Moon	Sun
T_ant	200	1000	15	285
obs. ON/OFF ratio [dB]	3.4	8.3	0.3	3.1
T_system	163	170	170	270
T_backgrd	3	3	3	3
ON/OFF ratio [dB]	3.40	8.30	0.29	3.08

In the following table we collect all the relevant quantities for the Sun and Moon, using the parameters for the ESA dish after the repair:

	Sun	Moon	
Temperature	16000	200	K
Radius	$7.0\ 10^{5}$	$1.74\ \ 10^{3}$	km
Distance	$1.5\ 10^{8}$	$3.84\ 10^{5}$	km
Angular diam.	0.5	0.5	deg
Solid angle	$6.84\ 10^{-5}$	$6.42\ 10^{-5}$	sr
Frequency	11	11	GHz
Wavelength	2.73	2.73	cm
Intensity	$5.94\ 10^{10}$	$7.42\ 10^{8}$	Jy/sr
Flux	4.06	0.0477	M Jy
Dish diameter	1.2	1.2	M
HPBW	1.32	1.32	Deg
Cross section	1.13	1.13	m^2
Area ratio	0.0988	0.0756	
Efficiency	0.75	0.75	
Effective area	0.848	0.848	m^2
T_ant	1248.36	14.65	K

Solar Flux:

The antenna temperature with the repaired ESA-Dresden telescope is about 1000 K. Taking the antenna's effective area A_{eff} as 0.84 m², as deduced by the designers, this gives a flux of the Sun of:

$$\text{Flux} = 2\ P_{received} / A_{eff} = 2\ \text{k}\ T_{ant} / A_{eff}$$
$$= 3.3\ 10^{-20}\ \text{W/m}^2\text{/Hz}$$

which is slightly smaller than the true value of $4\ 10^{-20}$ W/m²/Hz found by professional observatories (e.g. Learmont Obs., quoted in the designers' Calibration Report). Such a value would give an antenna temperature of 1200 K. This difference simply reflects the overall uncertainties of our instrument, the flux calibration, and the present observational procedures which still need to be optimised.

Value of the prototype derived by the designers:

In their Calibration Report, the designers use the measured flux from the Sun of

$$\text{Flux} = 402.1\ 10^{-22}\ \text{W/m}^2\text{/Hz} = 4\ 10^{-20}\ \text{W/m}^2\text{/Hz}$$

and the antenna effective area, estimated from the gain of an equivalent telescope of

$$A_{eff} = 0.84\ \text{m}^2$$

With the measured solar signal of 53.5 dBµV (at 16:20 on 5 aug 2005) and the off-source level of 44.9 dBµV, they get

$$T_{sys} = 310\ \text{K}$$

This is about twice as high as our ground-calibration based determination. However, in their Eq. (5)

$$T_{ant} = \frac{Flux \cdot A_{eff}}{k},$$

a factor of 2 is missing which accounts for the fact that the LNB receives from the unpolarized radio emission only one linearly polarized component. If we correct for this, we get

$$T_{ant} = \frac{Flux \cdot A_{eff}}{2 \cdot k},$$

This gives for the system temperature

$$T_{sys} = \frac{Flux \cdot A_{eff}}{2 \cdot k} / \left(\frac{P_{source}}{P_{backgrd}} - 1 \right)$$

which now yields values of about 150 … 200 K, in agreement with our determinations.

Implications for Observations of the Moon:

The preceding analysis shows that the ESA-Dresden telescope at ISU has indeed the same system temperature as the prototype. It also demonstrates that two instruments of this type do have the same reproducible performance, and that a successful installation and operation of the ESA-Dresden telescope at other institutions can be expected.

One of the great challenges is the observation of the Moon. As is seen from the tables above, a lunar surface temperature of about 200 K (taken from the observations of Monstein (1987)) gives an antenna temperature of about 15 K, and an on-source/off-source power ratio of only 0.3 dB. The typical dispersion of level values during a calibration, viz. at constant input signal, is found to be 0.1 dB – the discretization of the dB values also occurs on that level. This shows that it is rather difficult to identify the lunar signal as a slight enhancement of the signal at some sky position, seen against the random fluctuations of the measured values. Since the positioning system cannot be expected to allow a blind setting on the expected lunar position with sufficient accuracy to find the moon at the centre of the antenna beam, the observer cannot but search a small region of about 2 degrees for this slight enhancement!

In a full scan of the lunar passage, one has about 200 data points which are compared to a theoretical profile. This is equivalent to averaging the noise fluctuations over all these points. Hence, the noise amplitude is reduced by a factor of $\sqrt{200}$ = 45. One may thus estimate the accuracy of the lunar flux as about 0.1dB/45 = 0.002 dB. However, this error is negligible in comparison with the uncertainties introduced by the difficulties to subtract properly the background

As shown by Monstein (1987), the variation of the flux with the lunar phase is quite limited, having the amplitude of about 20 K about a mean value of 200 K. Therefore, the ESA-Dresden telescope is able to pick up the moon at any lunar phase, however at about 0.3 dB above the background, if there are no rain clouds dominating the emission in that region of the sky. The observations conducted by the designer showed mostly half scans with the signal going down by about 0.5 dB as the Moon moved out of the antenna beam. A few observations gave a level change of 1 dB, including the three-quarters scan shown in the documentation. However, these observations were neither flux-calibrated nor conducted long enough to find a really constant background. And the changes in the signal level are not consistent with the expected values derived from the lunar flux of 50 kJy which is in agreement with the temperature from Monstein (1987) as well as our own calibrated measurements.

Because of the factor 2 for the correction of polarization, the relation used by the designers to predict the measured signal differences

$$(dB_{source} - dB_{backgrd}) = 10 \cdot \log\left(1 + \frac{Flux \cdot A_{eff}}{k \cdot T_{sys}}\right)$$

Since the correct formula gives the same value for half the system temperature, application of the correct system temperature results in exactly the same values. Thus one obtains for the Sun 9.47 dB and the Moon 0.41 dB. For the system temperature of 170 K of the instrument at ISU one obtains the somewhat smaller values listed in one of the above tables.

Issues to be resolved:

It remains to be found out why the designers claimed to have measured a lunar flux of 10 kJy: with Tsys = 310 K and this value for the flux, one would get a signal enhancement of only 0.08 dB … which is not in accord with their observations and the capabilities of the instrument. It appears that a factor 10 in the fluxes had been skipped, so that in fact they had deduced a flux of 100 kJy, about twice as large as the published value. It also seems more reasonable to accept that with a larger system temperature one would overestimate the flux.