Calibration Report

Author: Uwe Knöchel
Frank Haiduk
Fraunhofer Institute IIS

Project: **Radio Astronomy at Schools**
Workpackage 4

Contract: 18369/04/NL/CP
ESA contact: Ravinder Bhatia, ESTEC TEC-MCT

Contractor: Fraunhofer-Institut für Integrierte Schaltungen, Erlangen
Außenstelle Entwurfsautomatisierung
Zeunerstr. 38
01069 Dresden, Germany
http://www.eas.iis.fraunhofer.de/

Date: 08 August 2005

Abstract

This report describes the calibration of the school radio telescope. Section 2 outlines the theory of radio telescope operation. By executing a Sun observation the unknown system temperature can be determined. With this parameter, the performance of the telescope can be estimated (section 3). The calibration data and initial observation results are given in the Appendix.

Content

Terms and Abbreviations

Aeff	effective antenna aperture
AMA 300	used receiver device
AZ-EL	azimuth-elevation (coordinate system)
B	bandwidth
dBμV	voltage in decibel referenced to 1μV
G	isotropic antenna gain
LNB	low noise block converter
P	signal power
R	input resistance of receiver
S	flux in Jansky
Tant	antenna temperature
Tsys	system temperature
U	signal voltage
Y	power quotient on source / off source

1 Introduction

Why we need calibration? A very demonstrative motivation of calibration was found in 1:

> *As you likely know, every telescope is unique. One result of the uniqueness of individual telescopes is the difficulty of directly comparing measurements from one telescope with those from another. That is, Telescope A may record 280 counts for the peak of a given spectral line, while Telescope B may record only 100 counts. This is further complicated by the fact that even measurements taken on a given telescope, at a given frequency, can change over time. These changes can be the result of changes in, e.g. the telescope system temperature, the telescope response, and/or the atmospheric conditions. This means that even if you only observe your object with Telescope A, but measure it repeatedly over a year, you may discover that your object's peak count varies from 280 one day to 250 or 300 on another day, and so forth. You then need to understand whether the source emission is truly varying with time or if the differences are due to changes within the telescope and equipment.*
>
> *In order to compare measurements between two telescopes, or even between one telescope taken at different times, we need a universal measurement system. That is, we need to be able to state that 280 counts from Telescope A is equivalent to X counts from Telescope B or equivalent to Y counts from Telescope A at a different epoch. This is the process of data (or telescope) calibration, and the rest of this chapter will be devoted to presenting the various methods available, both observationally and theoretically, to calibrate data.*

The task for calibration is to determine how the measured voltage levels are related to the flux of the observed sources.

2 Calculations for Radio Telescopes

2.1 Relation between measured voltage level and flux

For cost reasons the telescope shall be calibrated without a local noise reference source. The receiver itself is calibrated and displays the incoming signal voltage level U in dBuV units. The voltage level is referenced to a resistance R of 75 Ohms. Hence the linear power of the received signal can be calculated:

(1) $U[\mu V] = 10^{\frac{U[dB\mu V]}{20}}$ and $P[W] = \frac{U^2}{R}$

If the telescope is pointed to a radiation source the power P is measured. Pointed away from any source a base power level P_0 is measured mainly caused by the noise of the telescope parts. The ratio between the power on source and off source is referred to as Y-factor. It can be computed from the on source (UdB) and off source (U0dB) signal level values expressed in dBµV as follows:

(2) $$Y = \frac{P}{P_0} = 10^{\frac{UdB - U0dB}{10}}$$

The Y-factor is related to the antenna temperature of the observed source T_{ant}, the temperature of the cold sky T_{cold} and the system temperature T_{sys} in the following way:

(3) $$Y = \frac{T_{sys} + T_{ant}}{T_{sys} + T_{cold}}$$

For our telescope operated at ambient temperature we can assume that T_{sys} is much larger than T_{cold}. Therefore:

(4) $$Y = \frac{T_{sys} + T_{ant}}{T_{sys}}$$

T_{ant} can be determined for a known flux S as follows:

(5) $$T_{ant} = \frac{S \cdot A_{eff}}{K},$$

where A_{eff} is the effective antenna aperture or the effective area of the antenna. Due to imperfections of the shape of the antenna, the effective aperture is smaller than the geometric size of the antenna. K is the Boltzmann constant equal to 1.38e-23 J/K.

From equation 2, 4 and 5 we get the relation between the measured power value and the flux of the source:

(6) $$\frac{P}{P_0} = \frac{T_{sys} + \frac{S \cdot A_{eff}}{K}}{T_{sys}} = 1 + S\frac{A_{eff}}{K \cdot T_{sys}}$$

Solved for S:

(7) $$S = \left(\frac{P}{P_0} - 1\right) \cdot \frac{K \cdot T_{sys}}{A_{eff}}$$

Equation 6 shows, that the sensitivity of the telescope depends on A_{eff} and T_{sys}. The sensitivity increases if a larger antenna is used or if the system noise temperature is reduced.

To estimate the sensitivity of our telescope, it is necessary to determine A_{eff} and T_{sys}. Since the antenna is relatively small and solid we expect no significant changes of A_{eff} over the time. T_{sys} depends on the ambient temperature. Therefore it must be measured before the observations for calibration purposes.

2.2 Determinination of Aeff

The effective antenna aperture Aeff can be calculated with the following equation, taken from 2:

(8) $G = \frac{4\pi A_{eff}}{\lambda^2}$

G is the isotropic gain of the antenna, given in some datasheets of the antenna. λ is the wavelength, where the dish is operated.

(9) $A_{eff} = \frac{G \cdot \lambda^2}{4\pi}$

2.3 Determinination of Tsys

With the knowledge of A_{eff} and the observation of a radio source with known flux, the system temperature can be calculated. Some well known point sources like Cassiopeia are used as calibration sources, since there flux is very stable. Due to the limited sensitivity we want us the Sun as calibration source. In contrast to A_{eff}, T_{sys} will change over the time. Therefore the calculated value is valid for a short period only. Nevertheless it may be an interesting task for students to perform a calibration.

Equation 6 solved for T_{sys} provides:

(10) $$T_{sys} = \frac{\frac{S \cdot A_{eff}}{K}}{\frac{P}{P_0} - 1}$$

2.4 Discussion about resolution and integration time

The resolution 11 or minimum measurable temperature increase 12 of a radio telescope can be calculated by the "Dicke" expression 3.

(11) $$\frac{\Delta P}{P} = \frac{1}{\sqrt{B \cdot \tau}}$$

(12) $$T_{\min} = \frac{T_{sys}}{\sqrt{B \cdot \tau}}$$

Where B is the bandwidth and τ is the measurement integration time. The expressions 11 and 12 show, that the sensitivity can be improved by increasing bandwidth and integration time.

Because this school radio telescope is based on the AMA 301 receiver, there is now option to change the bandwidth and integration time. The receiver bandwidth is about 20MHz in the used Sat-TV mode. This is a high bandwidth compared with ham radio receivers used in other radio astronomy projects. In the datasheets of the receiver there is unfortunately no information about integration time and measurement of the signal strength. After warm-up the absolute accuracy of the measurement is specified with +/- 1 dBµV, the values are provided with 0.1 dBµV resolution.

The accuracy of the power measurement can be increased by computing the mean value of a number of single measurements. It requires an accurate tracking of the object position on the sky, which can be realized by using the tracking feature. To observe a weak radio source, a high absolute pointing accuracy of the telescope is additionally needed. It must be ensured, that the telescope is pointed to the source, before the long term integration shows a small increasing of recorded signal level. This accuracy is not provided by any rotator unit in a reasonable prize range.

3 Calibration and Evaluation of the Telescope

3.1 Computation of Aeff

The effective antenna aperture Aeff is calculated as described in section 2.2. Unfortunately the manufacturer of our dish does not provide a value for the isotropic antenna gain G. The data of a similar antenna by Hirschmann are used instead:
G is 41.5 dBi at 10.95 GHz, which corresponds to a wavelength λ of 2.7378e-2m.

$$A_{eff} = \frac{G \cdot \lambda^2}{4\pi} = \frac{10^{41,5/10} \cdot \left(2.74e^{-2}\right)^2}{4\pi} = 0.842546m^2$$

The geometric size of a 1.20m antenna is about 1.13m^2. As expected, the effective antenna size is smaller. Therefore the efficiency factor of the antenna is 0.745. This value is in the expected range.

3.2 Calibration of Tsys with Sun observation

The results of a Sun observation (see Appendix 5.2 and 5.5) and reference values for the radio flux of the Sun at several frequencies (see Appendix 5.1) are used with equation 10 to determine the current value of T_{sys}.

The observation of Sun gives the for example the following values:

Parameter	Value	Comment
S	402.1 sfu	1sfu = 10000J = 10^{-22} W/m^2/Hz See Appendix 5.1 and 5.5
Aeff	0.8425m^2	See 3.1
K	1.38^{-23} J/K	Boltzmann constant
P	53.5 dBuV	See Appendix 5.5 (2005-08-05 – 16:20)
P_0	44.0 dBuV	See Appendix 5.5 (2005-08-05 – 16:20)

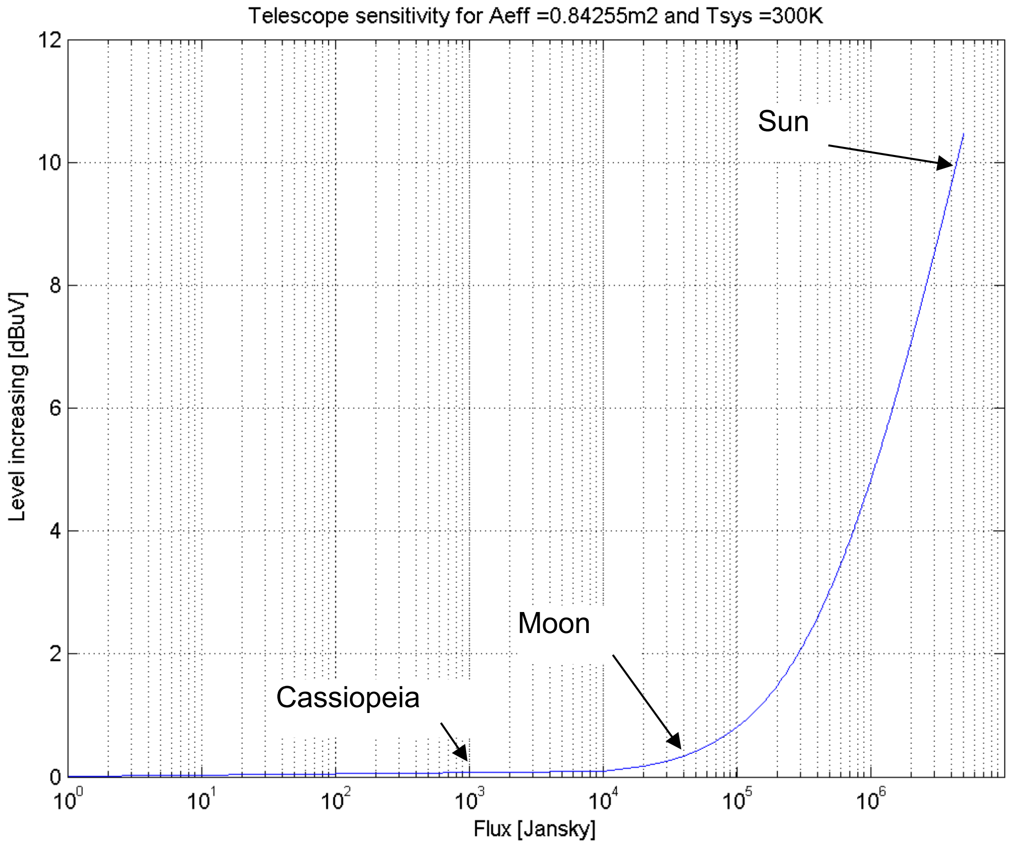
With this data we compute a system temperature T_{sys} of 310.0 K.

3.3 Estimation of telescope sensitivity

The increasing of voltage level measured at the receiver while pointing from the cold sky to a radio source with the flux S can be computed from equations 2 and 6:

$$UdB - U0dB = 10 \cdot \log\left(1 + S\frac{A_{eff}}{K \cdot T_{sys}}\right) \tag{13}$$

With the values for T_{sys} and A_{eff} computed before and the flux value of Cassiopeia A at 10 GHz of 1000 Jansky, we can predict the signal level at the receiver. Pointing to Cassiopeia the signal level will be increased about 0.009 dBµV compared to the cold sky. This weak signal cannot be detected in a direct way, because it is below the resolution of the device of 0.1dBµV. Averaging between numbers of single measures can increase the resolution, but this method is difficult to use due to the restricted pointing accuracy of the telescope (also discussed in section 2.4. The figure shows the estimated signal level at the receiver versus the flux value of the observation object. The graph depends on the system temperature T_{sys} which varies on environmental properties such as temperature.



3.4 Validation of the results at Moon observation

Using equation 7 with the observation data of the moon (see appendix 5.5) we compute the flux of the moon to about 1.0e+004 Jansky. The intensity of thermal radiation of the Moon depends on the Moon phase 4. Accurate radio flux values of the Moon could not be found on the Internet and in publications. A raw value can be taken from a diagram published in 2. The published value of about 5.00e+4 Jansky is above the value observed with our telescope.

Source of the difference between published and observed flux value can be:

- The dish is not pointed exactly on the radiation source while measure the on source level (the maximum was not captured)
- Terrestrial radio sources as telecommunication services, near buildings can influence the results at telescope location in a city area.
- The diagram 2 does not provide an accurate reference value for the flux of the Moon.
- Heating of the LNB while pointing to the Sun at days with clear weather

4 References

[1] K. O'Neil: **Single Dish Calibration Techniques at Radio Wavelengths**, Published in "The NAIC/NRAO School on Single Dish Radio Astronomy" C. Salter, et.al eds. 2002 (PASP), http://arxiv.org/abs/astro-ph/0203001

[2] G. Roth: **Handbook for planet observers**, Faber, 1970, also available in German

[3] L. Cupido: **EME and Radio Astronomy**, http://w3ref.cfn.ist.utl.pt/cupido/eme_ra2.pdf

[4] Chr. Monstein: **The Moon's Temperature at Lambda=2.77cm**, http://e-collection.ethbib.ethz.ch/ecol-pool/bericht/bericht_87.pdf

5 Appendix

5.1 Reference data for Solar fluxes

The Learmonth Observatory (Australia) provides daily solar flux data on the Internet:

http://www.ips.gov.au/Solar/3/4/2

The fluxes are measured at several frequencies from 245 MHz up to 15.4 GHz. Between the observed values some other frequencies are interpolated. The values represent the quite Sun. If bursts are detected this frequencies are not useful for interpolation. The flux is given in solar flux units (sfu).

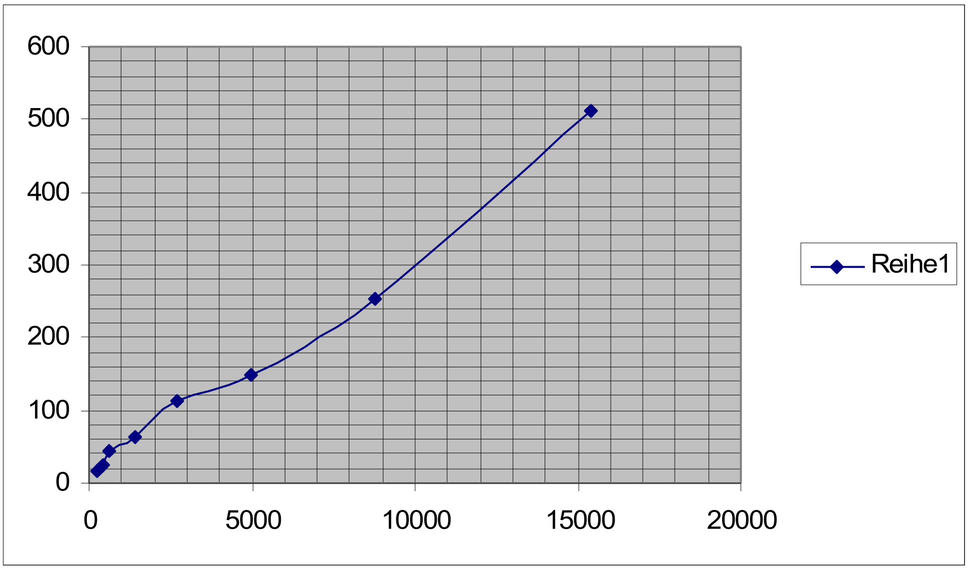
1sfu = 10000 Jansky = 10^{-22} W/m^2/Hz

The data from Learmonth observatory are provided in the format shown below.

Quiet Solar (IFLUX)

```
Last updated 05 Aug 2005 07:30 UT

IFLUX : Background Solar Radio Flux
-----------------------------------

Station      Date     Time    Status    Freq    QS flux    Quality
Learmonth  05/08/5    03:48    final     245      17       ? burst
                                         410      24         good
                                         610      44         good
                                        1415      63         good
                                        2695     114         good
                                        4995     149         good
                                        8800     253         good
                                        15400    512         good


================================================================================

Interpolated value for 1300MHz: 60.8
Interpolated value for 1540MHz: 68.1
Interpolated value for 1707MHz: 74.9
Interpolated value for 2300MHz: 98.5
Interpolated value for 2401MHz: 102.5
Interpolated value for 2790MHz: 115.7
Interpolated value for 5625MHz: 166.5
Interpolated value for 6000MHz: 176.9
Interpolated value for 8000MHz: 231.4
Interpolated value for 8200MHz: 236.8
Interpolated value for 10400MHz: 312.3
```

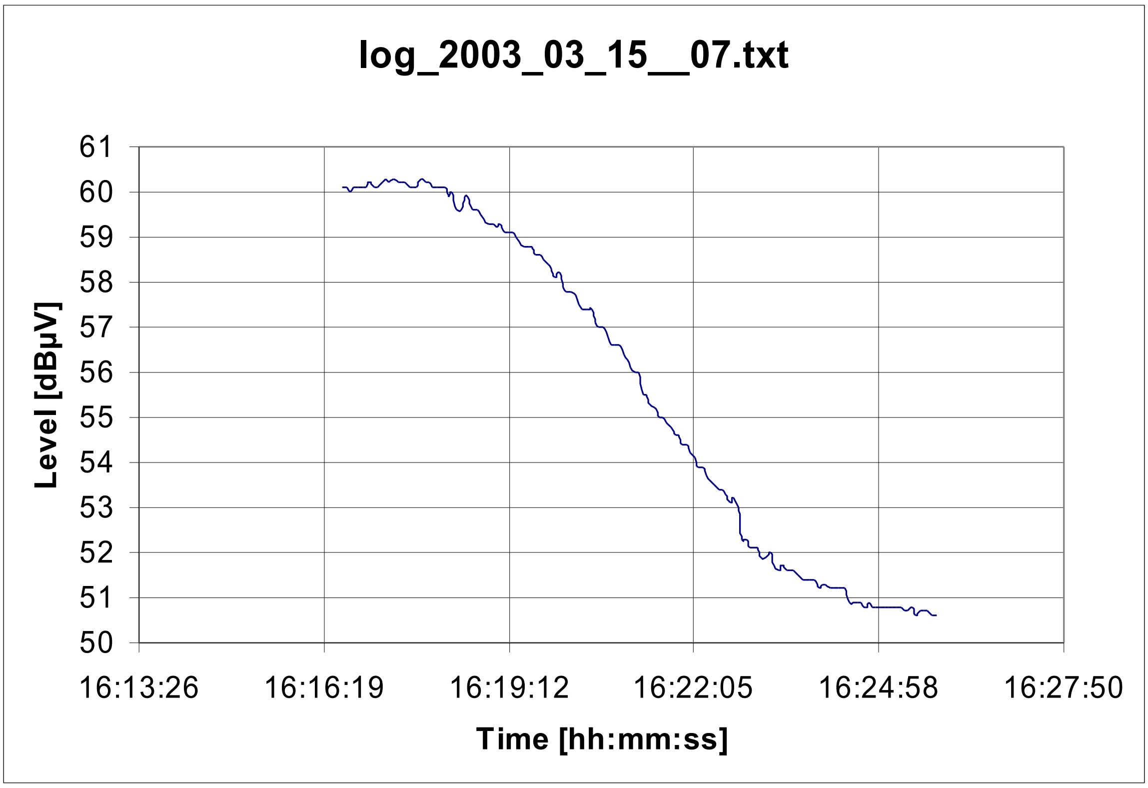
For our frequency of 12.6GHz we estimate a flux of about 402.1sfu by linear interpolation of the data in Excel.



An alternative Internet resource for radio flux values of the Sun is:

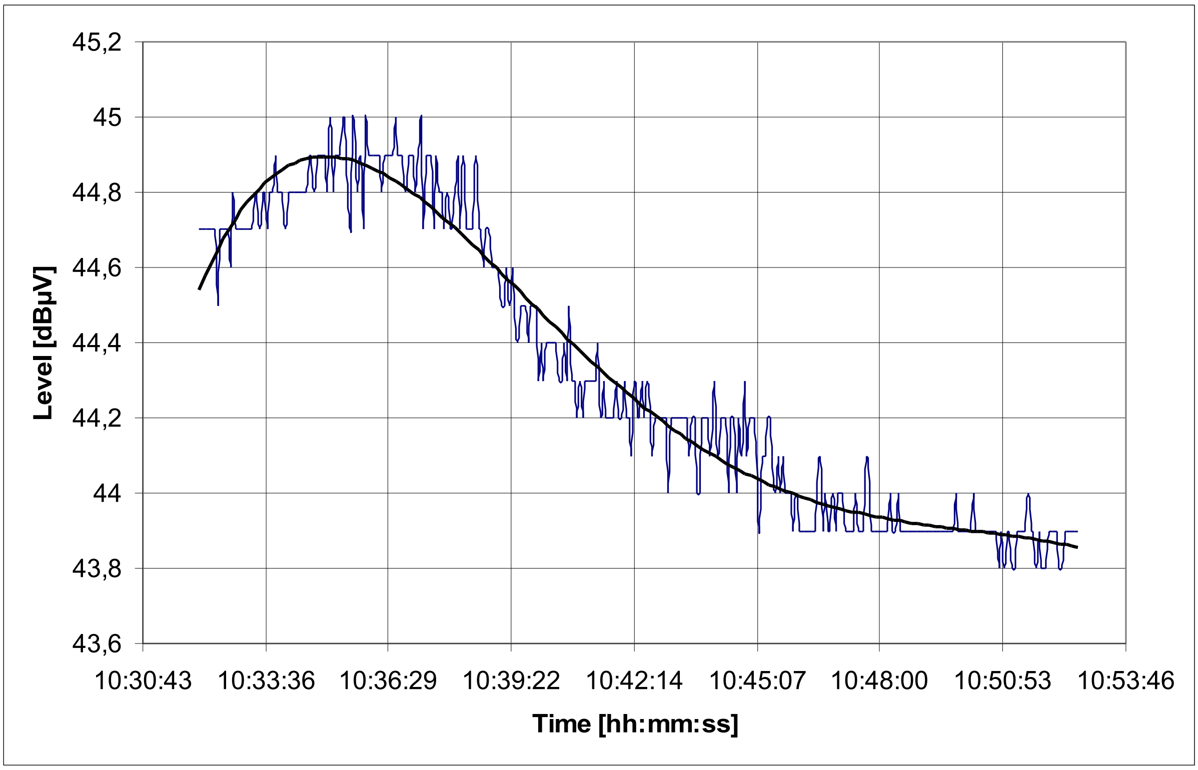
http://www.sec.noaa.gov/ftpdir/lists/radio/7day_rad.txt

5.2 Sun observation data (sample)



Sun Measurement, Freq.= 12600 MHz, SAT-IF= 2000 MHz, High Band, Horizontal Polar.

5.3 Moon observation data (sample)



5.4 Matlab script for the computation of the parameters

The m-File "calib3.m" contains:

- the computation of T_{sys} based on a Sun observation
- a plot of the telescope sensitivity
- estimation of Moon and Cas A signal values

The script can be used with *Matlab* (commercial software for technical computing) or *Octave*, a free Matlab clone available under Gnu Public License (GPL), distributed with Linux.

```
%Radioastronomie at Schools
%Computation of System temperature

%Parameters of the telescope
Aeff=0.842546;          %effective antenna aperture m2
K=1.38e-23;             %Boltzmann J/K
R=75;                   %resistance (not used)

%Observation results
UdB=60.3;               %Level measured for Sun [dBuV]
U0dB=50.8;              %Level measured for cold sky [dBuV]
Ssun=400.e-22;          %reference for Solar flux from Internet

UmdB=44.9;              %measured value for Moon dBuV
U0mdB=43.9;             %measured value for cold sky near Moon dBuV

% CALIBRATION WITH SUN
%----Computing Y faxtor linear------
```

```
Y=10^((UdB-U0dB)/10);
disp(['Ysun (lin) =', num2str(Y)]);

%----Computing System temperature-----
t1=Y-1;
t2=Ssun*Aeff/K;
Tsys=t2/t1;
disp(['Tsys =', num2str(Tsys)]);


%ESTIMATE THE SENSITIVITY OF TELESCOPE

%compute a sweep of flux values
S_ja=1:10000:5000000;
S=S_ja*1e-26;

%estimated signal level in dBuV vs. flux
dU_log=10*log10((S*Aeff/(K*Tsys))+1);

%plot the results
plot(S_ja,dU_log);
title(['Telescope sensitivity for Aeff =', num2str(Aeff), 'm2 and Tsys =',
num2str(Tsys), 'K']);
xlabel('Flux [Jansky]');
ylabel('Level increasing [dBuV]');
grid on;


%ESTIMATION OF FLUX VALUES FOR CASSIOPEIA

%which voltage level gives Cassiopeia at the receiver?
Scas=1000e-26;            %tabulated flux for cassiopeia
dP2log_cas=10*log10((Scas*Aeff/(K*Tsys))+1);
disp(['Estimated level for CAS A at 10GHz (dBuV) =', num2str(dP2log_cas)]);


%VALIDATION WITH DATA FROM MOON OBSERVATION
Ym=10^((UmdB-U0mdB)/10);  %Y-factor linear

t3 = K*Tsys/Aeff;
t4 = Ym-1;

Smoon = t4*t3/10e-26;
disp(['Calculated Moon flux (Jansky) =', num2str(Smoon)]);
```

5.5 Observation Data

Date	Time	Frequency	Object	On Source [dBµV]	Off Source [dBµV]	Solar Flux [sfu]	Computed Tsys [K]	Computed Flux of Moon [Jansky]	Weather	Comments
2005-08-04	14:44	12600(V)	Sun	51.7	43.0	407.0	387.42		Cloudy, 20 C	Tsys to high. Maximum probably not captured
	14:58	12600(H)	Moon	44.4	43.7			11099.6		
	15:09	12600(H)	Moon	44.5	43.6			11844.5		
	15:37	12600(H)	Sun	53.2	43.7	407.0	314.0			
2005-08-05	15:15	12600(H)	Sun	54.0	43.8	402.1	259.2 to low?		Sunny, 20 C	Power level jumped during the measurement, value may be corrupted
	15:32	12600(H)	Moon	44.1	43.2			9776.0		
	16:11	12600(H)	Moon	44.6	43.9			8888.0		
	16:20	12600(H)	Sun	53.5	44.0	402.1	310.0			
	16:34	12600(H)	Moon	44.5	43.9			7528.9		
2005-08-08	15:00	12600(H)	Sun	53.3	43.6	399.0	292.4		Sunny and Clouds, 16 C	
	16:20	12600(H)	Sun	53.7	44.0	399.0	292.4			
	16:33	12600(H)	Moon	44.7	44.0			8377.0		
2005-08-09	13:43	12600(H)	Sun	43.3	52.2	390.7	352.7		Sunny 18 C	Receiver Warm-up?
	14:11	12600(H)	Sun	42.4	51.7		317.6		Clouds 18 C	Full transit
	14:30	12600(H)	Sun	42.3	51.2		352.7		Clouds 18 C	On-off measurement
	14:33			42.2	51.3		334.6			
	14:35			43.2	52.2		343.6			
	14:50			43.2	52.1		352.7			
2005-08-11		12600(H)	Sun	42.0	51.5	390.7	301.3		Clouds 20 C	

Solar Flux values are used from the Learmonth observatory see section 5.1.