Radioastronomy with a TV-satellite dish

Lab Course M at I. Physics Institute of the Universität zu Köln

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1 Introduction

The aim of the experiment *Radioastronomy with a TV-satellite dish* is to determine the temperature of the sun. With the small radio telescope on the roof of the institute we measure radiation emitted by the sun. To interprete the measured data and to finally determine the physical temperature, we need to calibrate the measurement system.

This experiment relies on the knowledge taught in the experiment *Microwave Radiometer*. Therefore, it is advisable to work through these two experiments in the appropriate sequence.

The basic knowledge of antenna physics and the physics of electromagnetic radiation need to be prepared in advance.

2 Preparation

In particular you should have a working knowledge of the following concepts:

2.1 Basics

- Black body radiation
- Rayleigh–Jeans approximation, Wien's law
- Absorption and emission of radiation
- Basics of celestial mechanics, satellite orbits
- Optics: single slit diffraction

We recommend to use radioastronomical literature for the preparation [1, 2], since they emphasize the connection between the fundamental laws of physics and their application in astronomy.

2.2 Specific concepts and techniques of radioastronomy

These topics should be prepared with the help of the literature cited below.

- Reciprocity theorem
- The sun as a radio source
- The atmosphere's influence on electromagnetic radiation (radio window)
- Airmass (path length through the atmosphere)

- Antenna pattern
- Techniques to determine the antenna pattern
- Correction factors (efficiencies) in the antenna pattern
- Antenna temperature
- Relationship between the antenna pattern and the contributions to the antenna temperature
- Calibration of the antennea temperature
- Receiver noise
- Y-factor calibration
- Heterodyne principle.

The questions of section 3 should be prepared for the day of the experiment and need to be answered in the written report.

The report has to be submitted as hardcopy, and, if it is prepared using a typesetting program, the final version (after all corrections) also has to be submitted electronically (LaTeX, *OpenOffice* or *Word*-Format – not PDF).

2.3 Theory

Properties of the radiation In radio astronomy one normally deals with incoherent radiation. This means that the radiation consists of a mixture of statistically independent waves with different frequencies and phase.

Intensity The intensity of the radiation ist the crucial property in this experiment since it is directly proportional to the temperature. The spectrum of a black body is given by the Planck law. For not too low temperatures and not too high frequencies ($h\nu \ll kT$) the exponential in the Planck law can be approximated by a Taylor series. Ignoring all but the linear term one gets the Rayleigh–Jeans approximation. Figure 1 show the radiation spectrum of a black body.

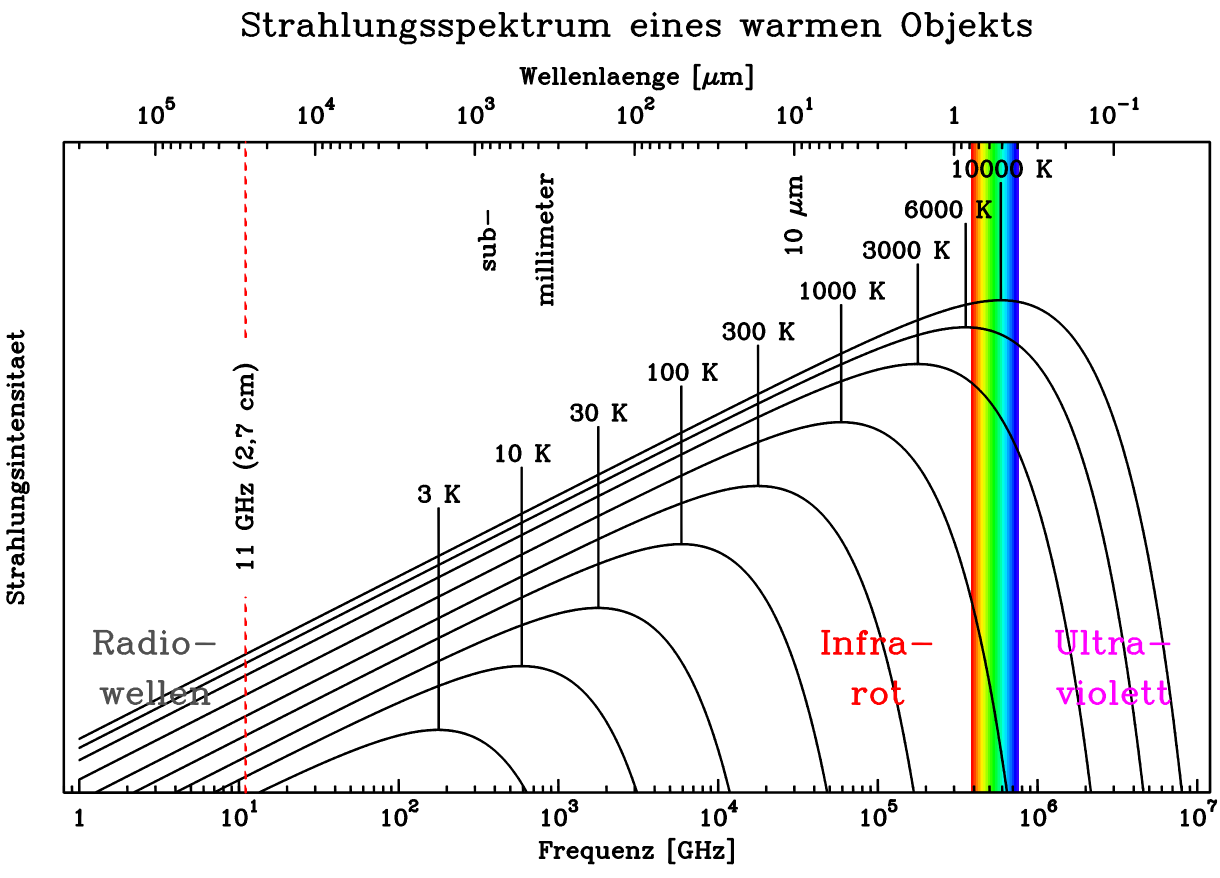

Figure 1: The radiation spectrum of a black body.

For our observing frequency of 11 GHz and an estimated temperature of the sun of approximately 6000 K we have:

$$\begin{aligned} \frac{h\nu}{k} &= 0,53\,K \\ T &= 6000K \end{aligned}$$

Obviously

$$\frac{h\nu}{k} \ll T\,,$$

showing that the Rayleigh-Jeans approximation is good enough. Within this approximation the intensity and temperature are directly proportional to each other. This is the reason that in radioastronomy the two quantities are often used synonymously.

Absorption und emission of radiation Although the intensity B is independent of the the distance to the source, it can be modified along the path of propagation x. Both absorption and emission may affect the intensity. The reduction of the intensity through absorption in a medium (e.g a cloud) is given by:

$$B = B_0 \, e^{-\tau_c}. \tag{1}$$

B_0 is the intensity before entering the medium, τ_c is the optical depth. For a constant absorption coefficient α of the medium τ_c may be written as αx. The emission by the medium is given by:

$$B_c = B_i \, (1 - e^{-\tau_c}). \tag{2}$$

B_i is the source function of the cloud's emission. Thus, a cloud that is both, emitting and absorbing, the total intensity is

$$B = B_0 \, e^{-\tau_c} + B_i \, (1 - e^{-\tau_c}) \tag{3}$$

Expressed in units of temperature this is:

$$T = T_0 \, e^{-\tau_c} + T_c \, (1 - e^{-\tau_c}), \tag{4}$$

where T_c is the temperature of the cloud. In a real case this equation describes for example the temperature of a source observed through the atmosphere.

The reciprocity theorem The reciprocity theorem state that the radiation characteristics of an antenna is idependent of whether it is used as a receiving or a transmitting antenna. This is equivalent to the fact that in optics a light path can be reversed.

Antenna calibration The voltage measured by the ADC board in the measurement computer is directly proportional to the power received by the telescope.

$$V_{ADC} = c \, T_{sys} \tag{5}$$

$$T_{sys} = T_A + T_{rec} \tag{6}$$

T_{sys} is the system temperature, as measured through the receiver. it is composed of the receiver's intrinsic noise temperatur (T_{rec}) and the external signal T_A. c is a proportianality constant, which has to be determined by the calibration. T_{rec} can be obtained from the Y-factor calibration.

The antenna temperature T_A is the so called antenna temperature. To deduce the properties of the observed source from this quantity, one needs to know exactly the signals contributing to T_A (Abb. 5).

$$T_A = T_S^* + T_{Cosm}^* + T_{amb}^* + T_{atm}^*. \tag{7}$$

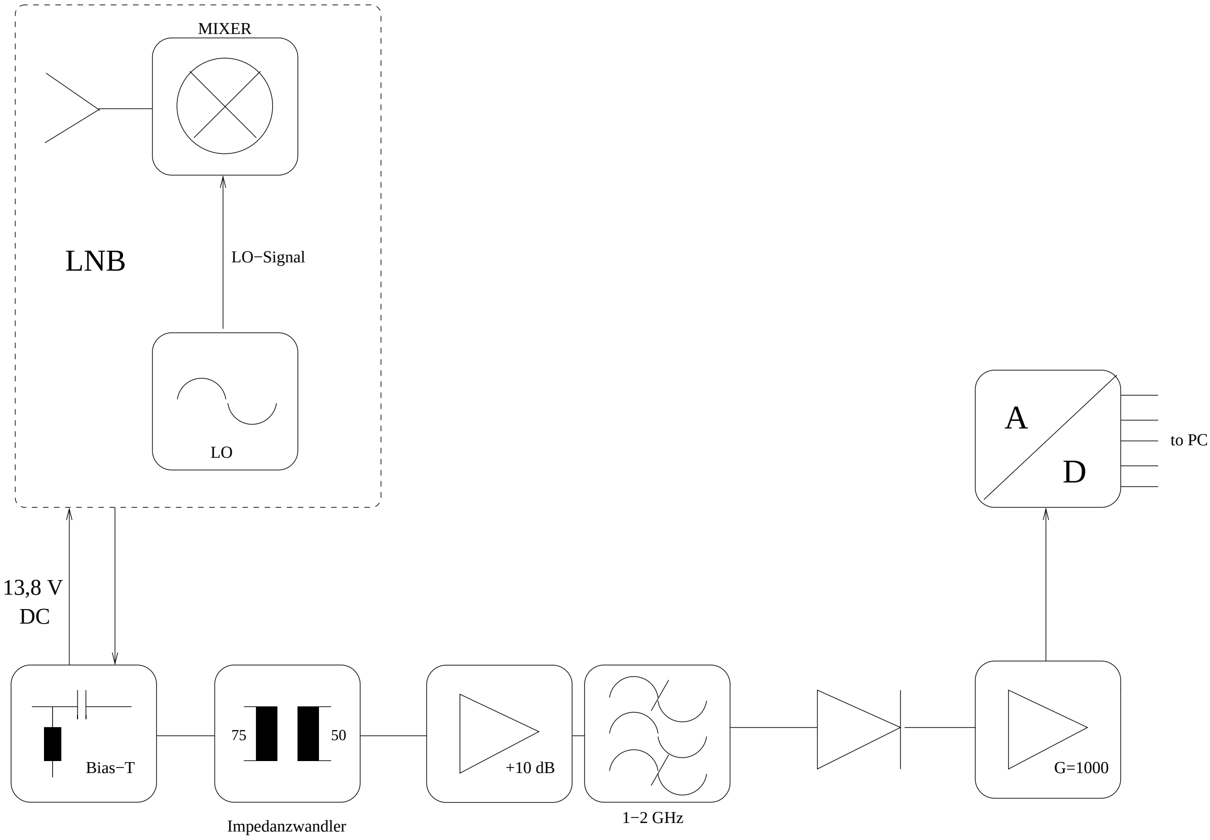

Figure 2: Functional schematics of the receiver

The firs term T_S^* accounts for the radiation from the source. T_{Cosm}^* is the contriburion by the cosmic background radiation (2.7K) seen by the antenna. T_{amb}^* accounts for the fraction of ambient temperature radiation reaching the detector (the LNB) from the surroundings of the antenna, e.g. the ground around the telescope. T_{atm}^* contains the temperature of the atmosphere es detected by the telescope. The *-marker indicates that the respective temperatures have to be corrected for their fraction contribution to the antenna temperature.

The antenna pattern The antenna pattern $P_n(\Omega)$ describes the relative directional sensitivity of the telescope. $P_n(\Omega)$ is normalized i.e. $P_n(0) = 1$. To be able to precisely calibrate the telescope, we need to know the antenna pattern over the whole sphere surrounding the telescope. The antenna pattern can be split in to major parts: the main lobe of the antenna and the minor lobes and scattering. The residual sensitivity outside of the main lobe results from diffraction at the antenna dish, from scattering and spill over. Spill over describes the fact that the LNB has some residual sensitivity beyond the edge of the dish. Thus, the LNB sees some radiation emitted by the ground surrounding the telescope (this is the T_{amb} contribution to T_A).
The antenna pattern may be determined in two ways. It may be calculated or measured.

correction factors (*efficiencies*) Quantitatively the parts of the antenna pattern ar described by 2 efficiencies, η_{fss} (*forward spillover and scattering*) and η_{rss} (*rearward*

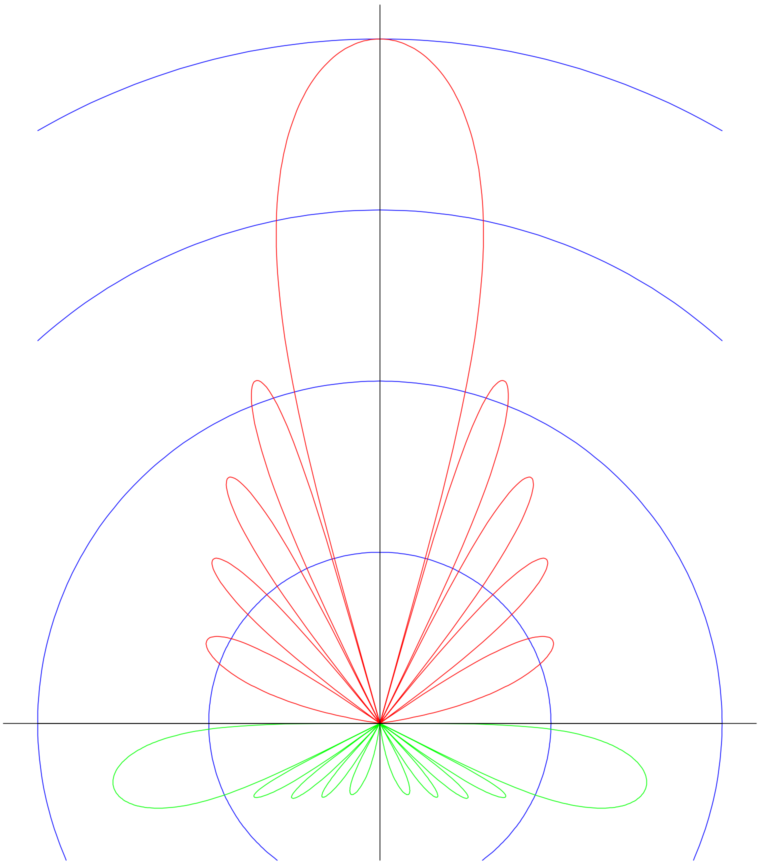

Figure 3: Schematic antenna pattern in polar (logarithmic) representation. The red part indicates the sensitivity in the forward half sphere, consisiting of main lobe and minor lobes. The green part represents the sensitivity in the rear half sphere, which is caused by spill over effects.

spillover and scattering):

$$\eta_{fss} = \frac{\iint_{\Omega_D} P_n(\Omega)\, d\Omega}{\iint_{2\pi} P_n(\Omega)\, d\Omega} = 66\% \tag{8}$$

$$\eta_{rss} = \frac{\iint_{2\pi} P_n(\Omega)\, d\Omega}{\iint_{4\pi} P_n(\Omega)\, d\Omega} = 87\% \tag{9}$$

Ω_D is the solid angle covered by the main lobe. The 2π integrals extend over the forward half sphere. Thus, η_{fss} is the fraction of power detected within the main beam compared to the total power detected from the forward half sphere. η_{rss} is is the fraction of power detected from the forward half sphere compared to the total power received.

For simplicity, we often approximate the main beam by a two-dimensional Gaussian distribution.

Coupling efficiency If the source is smaller than the main beam, we need to take into account that only a fraction of the radiation detected by the antenna originates from the source. Thus, we need to estimate, what fraction η_c of the main lobe is filled by the source: (Abb. 4):

$$\eta_c = \frac{\iint_{\Omega_D} T_{n,\mathrm{Source}}(\Omega)\, P_n(\Omega)\, d\Omega}{\iint_{\Omega_D} P_n(\Omega)\, d\Omega}. \tag{10}$$

$T_{n,\mathrm{Source}}$ is the normalized temperature distribution of the source. We assume a constant circular distribution, *i.e.* $T_{n,\mathrm{Source}}$ is equal to 0 within the area of the solar disk and 0 outside of the disk.

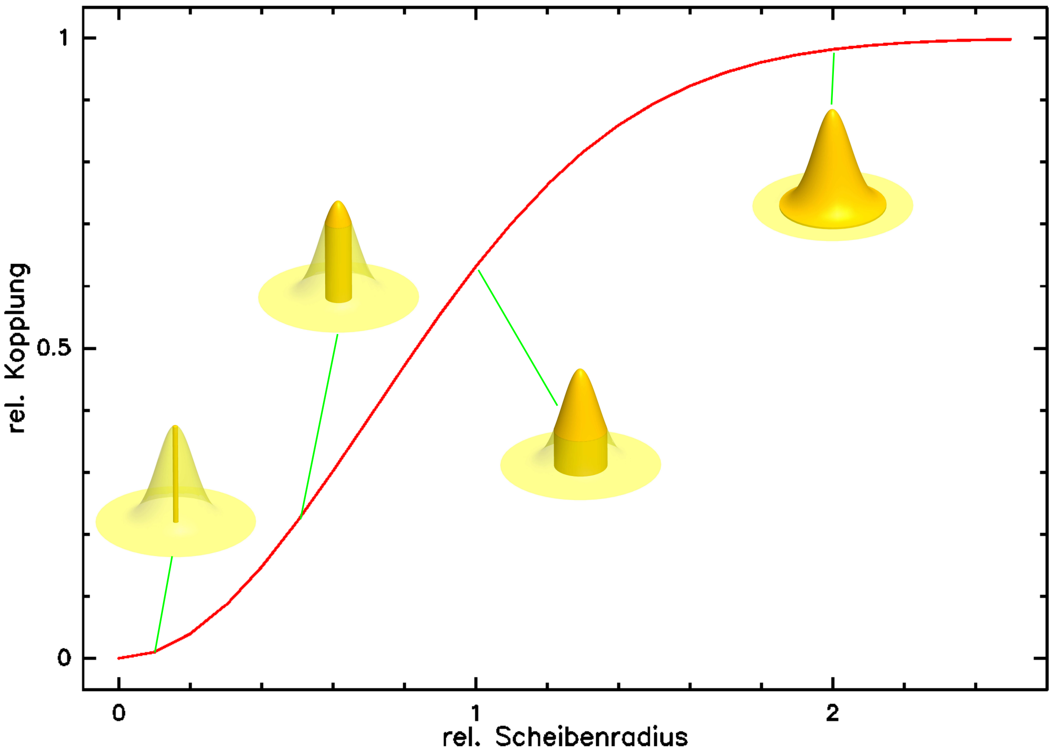

Figure 4: Coupling efficiency η_c versus source size expressed in units of the beam width. Only the dark colored fraction of the antenna pattern receives radiation from the source.

With the assumption of a Gaussian main beam and a disk-like source with constant temperature, it is possible to calculate η_c analytically.

Effects of the atmosphere When measuring with a ground based telescope, the transparency of the earth's atmosphere is a crucial factor. The atmospheric transmission depends strongly on the wavelength. There are mainly two atmospheric windows suitable for astronomic observations from the ground: the optical regime and the so-called radio window. The radio window covers the frequency range from approximately 20 MHz to 300 GHz. At the low frequency end, the electron density of the ionosphere limits the transmission. Ultra violet radiation from the sun partly ionizes the atmosphere. This creates free electrons, which block the propagation of radiation below a certain frequency.

The upper limit of the radio window at around 300 GHz originates from absorption by atmospheric molecules, such as water or oxygen. This is the reason to put observatories for mm-wave astronomy on on high mountain tops with thin and dry air.

Even within the radio window the atmosphere has a non-negligible effect on the radiation. Absorption, refraction and scintillation need to be taken into account. For our measurements with the TV satellite dish, mainly absorption and to a very weak extent refraction in the troposhere play a role.

To determine the atmosperic transmission, one uses equation 4: an atmosphere with transmission $t = exp(-\tau_{Atm}) < 1$ causes an emission of $T_{Atm} \cdot (1 - t)$. If one varies the pathlength through the atmosphere in a controlled way, the characterisic variation of the signal received allows us to calculate the optical depth of the atmosphere.

This is done by slewing the antenna in elevation from zenith to the horizon (skydip) and measuring the detected power versus the variation of airmass (*i.e.* the pathlength through the atmosphere expessed in units of the zenith pathlength.

This measurement is compromised by the variation of the spillover signal (why?) received from behind the dish. We correct for this by a second skydip measurement with the dish covered by an absorber.

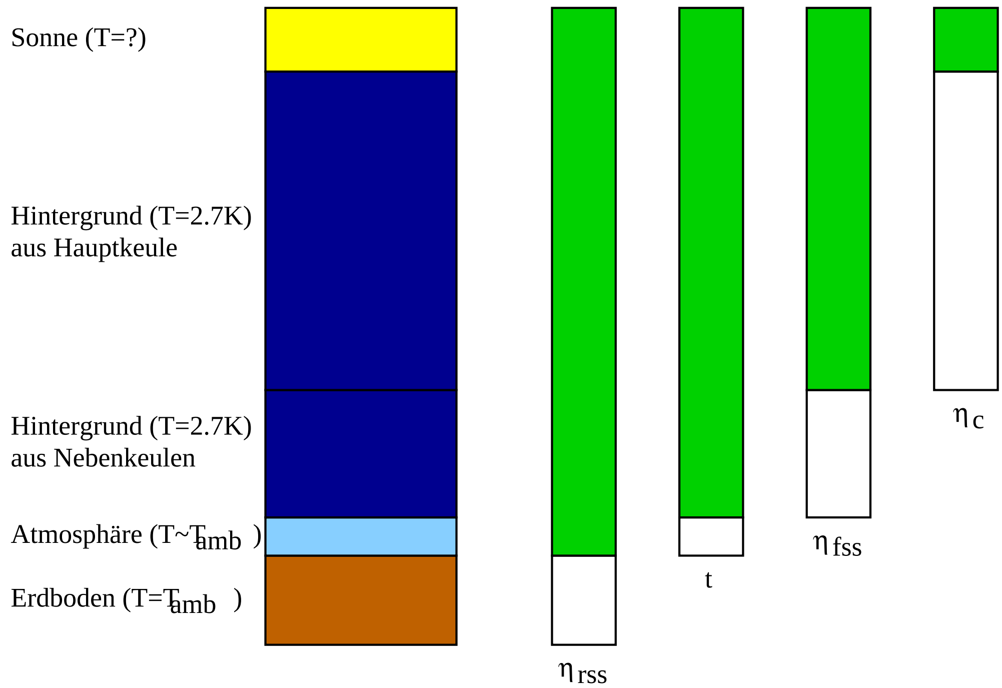

Figure 5: Visualization of the various contributions to the total signal received by the antenna.

The antenna temperature T_A Here we summarize the different contributions to T_A (Fig. 5):

$$T_A = T_S^* + T_{Cosm}^* + T_{amb}^* + T_{atm}^* \tag{11}$$

For the report, please determine the expressions for the individual corrected radiation temperatures T_i^* marked with an asterisk (*). Example:

$$T_{Cosm}^* = T_{Cosm} \cdot \eta_{rss} \cdot (1 - \eta_{fss} \eta_c) \cdot \exp(-A \cdot \tau_Z) \tag{12}$$

This means that the physical temperature T_{Cosm} for the forward direction gets corrected by a factor η_{rss} (87%) and for the atmospheric absorption by $exp(-A \cdot \tau_Z)$. The part of the radiation detected from the sun is subtracted.

Establish the corrections for the other contributions to T_A.

3 Questions

Answer the following questions. Make reasonable assumptions where required.

1. Give the orbital periods of some terrestrial satellites: ISS, ASTRA, moon. Calculate the respective orbital radii.
2. Estimate the width of the antenna main beam (Hint: reciprocity theorem, diffraction). The telescope diamter is 1 m.
3. Estimate the width of the antenna main beam of your eye (yes!). What does it mean?
4. Derive the formula for the coupling coefficient η_{c} assuming a Gaussian main beam and a concentric circular constant temperature source.
5. Estimate the coupling coefficient $\eta_{\mathrm{c,sun}}$ between the antenna main beam and the sun.
6. Estimate the coupling coefficient $\eta_{\mathrm{c,ASTRA}}$ between the antenna main beam and the ASTRA satellite.
7. What is the relation between atmospheric transmission and antenna elevation (fit function for the skydip measurement)?

4 Measurements

Carry out the following measurements:

1. Map a satellite. Required commands:
   `pos astra.in`: select a satellite as the source.
   `measure map 9 0.6`: Map the satellite (i.e. the antenna main beam) with a 9×9–pixel map using 0.6 degrees pixel spacing.
2. Calibration of the antenna temperature using liquid nitrogen and ambient temperature. Cover the detector's field of view first with a liquid nitrogen dewar and then with a room temperature absorber. The LNB shold be looking down, which can be achieved with the command `pos cal.in`. This makes the telescope slew to zenith. Data acquisition starts with the command `measure stare 500` ("Stare at whatever is visible for 500 seconds"). Before the calibration measurement the ambient temperature absorber should spend some time outside to reach a stable temperature. Measure the outside temperature with a thermometer.

3. Skydip:
   `pos skydip.in`: moves the antenna to a feature free part of the sky.
   `measure table skydip_2.table`: read offset positions from the file `skydip_2.table` and take a measurement at each position.

4. Repeat skydip with covered antenna. Cover the dish with the large absorber.

5. Map the sun: `pos SUN.in`, `measure map 9 0.6`.

We do the sun measurement several times. After this series, we repeat the calibration and the skydips. Try to make all measurement without unneccessary delay. Drifts in the measurement conditions by adversly affect your data.

5 Measurement data and report

First we determine the coupling efficiency between the sun and the antenna pattern. The coupling integral will be calculated analytically from the width of a Gaussian fit to the satellite map. The remaining efficiency factors are given above. The atmospheric transmission is obtained from the skydip measurement. First we have to subtract the rearward spill-over measurement from the actual skydip data. The function defined in section 3 is fitted to the resulting data to deduce the zenith optical depth.

Gaussian fits to the maps of the sun yield the difference of the antenna temperature measured on the sun and on the surrounding sky. Applying equation 11 in an suitable way to this difference, the temperature of the sun can be deduced.

To calculate the atmospheric transmission we use the zenith optical depth and the elevation of the sun during the measurement. If needed, the elevation can be reconstructed using the creation date of the data file of a measurement.

6 Using the system

The measurement setup is controled by a Linux PC, which communicates with the antenna drive system and digitizes the measurement data using an ADC extension board.

6.1 Processes

Several processes need to run during an observation to control and synchronize the subsystems:

- `astra_server` continuously calculates the position coordinates of the source. To be able to accurately track a moving astronomical object like the sun, it needs to know the exact time, which is ensured by an NTP network time sychronization.

- `tracker_server` controls the positioning of the antenna. It reads the coordinates calculated by `astra_server` and drives the dish to the desired position.

- `greg` is a data visualization program used in radio astronomy to graphically display the measured data.

6.2 Commands

- `pos`: Selects the object to be tracked. Syntax: `pos XYZ.in`. `XYZ` may be any of `SUN MOON astra hotbird eutelsat cal skydip`. `pos cal` puts the antenna in an orientation suitable for the hot-cold calibration where the LNB is accessible with the liquid nitrogen dewar. `pos skydip` selects an azimuth position where neither high buildings nor satellites are encountered.

- `measure`: Starts a measuerement. Syntax: `measure <command> X [Y]`, where `<command>` is one of the following:

  `h`, `help`: Display this message
  `c`, `cross`: Take a cross scan with X by X points spaced by Y
  `x`, `xline`: Take a horizontal line scan with X points spaced by Y
  `y`, `yline`: Take a vertical line scan with X points spaced by Y
  `m`, `map`: Take a map with X by X points spaced by Y
  `s`, `stare`: Take X measurements at current position, with a frequency of 1 Hz
  `t`, `table`: Take one scan at each offset in file X (or stdin)

  The data are stored in the directry `daten`, which is expected to be an existing subdirectory of the directory where `measure` measure was started.

- `Kset_fp`: Command to control low-level parameters of the system. This command is only used to correct pointing offsets, which may be encountered when changing sources. Syntax:

  - `Kset_fp`: lists all available parameters and their current values.
  - `Kset_fp <par>`: displays the value of parameter `<par>`. Relevant parameters are `a_poa` (pointing offset in azimuth) and `a_poe` (pointing offset in elevation).
  - `Kset_fp <par> <val>`: sets the value of parameter `<par>` to the value `<val>`. For instance `Kset_fp a_poe -2300` sets the elevation correction to -2300 arcseconds.

- `gaussfit`: Calculates the best fit Gaussian to a data set measured with `measure m N deg`. Syntax: `gaussfit < datafile`. The output contains the start values of the fit parameters and the best fit values. This out put may be redirected into a file using `gaussfit < datafile > fitfile`.

7 Literatur

References

[1] J. D. Kraus, *Radio Astronomy*, Cygnus-Quasar Books, 1986.

[2] O. Hachenberg and B. Vowinkel, *Technische Grundlagen der Radioastronomie*, Mannheim; Wien; Zürich: Bibliographisches Institut, 1982., Wien, 1982.

[3] "KOSMA: Kölner Observatorium für SubMillimeter Astronomie", (http://www.ph1.uni-koeln.de/gg/).

[4] "NANTEN2 (Chile)", (http://www.ph1.uni-koeln.de/workgroups/astro_instrumentation/nanten2/).

[5] "SOFIA: Stratosperic Observatory For Infrared Astronomy", (http://www.sofia.usra.edu).