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Bachelor of Science Astronomy

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SRON Netherlands Institute for Space Research

Calibration of a 11 GHz Pickett-Potter Horn

and measurements of the Cosmic Microwave Background

Willeke Mulder
S2359464

Thesis BSc Astronomy

Faculty of Mathematics and Natural Sciences
Kapteyn Institute and SRON
University of Groningen

Supervisors:
dr. J.P. (John) McKean,
Prof. dr. A. (Andrey) Baryshev
dr. R. (Ronald) Hesper

Second reader:
Prof. dr. M. (Marco) Spaans

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Abstract

This project is based on building a 11 GHz radio telescope, with the goal to measure the temperature of the Cosmic Microwave Background (CMB). The whole project was divided among four students which all focussed on different topics. In this thesis the calibration of the telescope is devised and tested. First a summary is given about the most important definitions that will be used during the project. Then, I will explain the importance of the atmosphere, in general and during our observations. In addition, the calibration before and during the observations is elaborated. The ultimate goal is measuring the opacity accurate enough to be able to measure the temperature of the CMB. After the first observation it turned that there has to be made a correction for the cold load. Because our entire beam was not filled by the liquid nitrogen, the temperature of the cold load turned out to be 10 K higher than the expected value that should have the temperature of liquid nitrogen, 77.14 K. After correction, I was able to measure an excess temperature of the of about 5 K in our system due to the CMB and systematics in the receiver temperature calibration. Further calibration tests will be needed to determine a precise value for the CMB.

Contents

1 Introduction

Nowadays, radio astronomy makes it possible to observe the Universe through the observation of electromagnetic radiation. In order to obtain information about stars and the interstellar medium in the Universe, electromagnetic radiation is the most commonly used source (Wilson et al., 2013).

For many centuries, observations of our Universe were limited. It was until 1931 when Jansky made the first observation of an astronomical radio source that astronomers only looked in the visible part of the spectrum. He started building an antenna that could receive radio signals. As the antenna could turn around, he was able to scan the whole sky. With these observations, he was able to measure the presence of nearby and distant thunder storms. Striking was the fact that there was a another unknown signal coming from the sky. Due to the fact that he measured the same signal every day, Jansky thought that he was measuring the Sun. Later on, he found out that the signal was not present every day, but every 23 hours, 56 minutes and 4 seconds. This specific period is also known as a sidereal day, which is the time that stars take to fully rotate around the Earth. This discovery allowed him to find out that the signal was not coming from our Solar System. It turned out that the radio signals were coming from the Milky Way. Due to this discovery, he got the nickname 'Father of Radio Astronomy'.

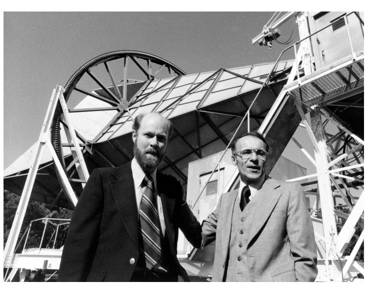


Figure 1.1: Left stands Robert Wilson and on the right is Arno Penzias. They are standing in front of the 20-foot Holmdel horn-reflector antenna.

Another big discovery in the field of radio astronomy, was the detection of an isotropic excess radiation. In 1965, the scientists Arno Penzias and Robert Wilson used the 20-foot Holmdel horn-reflector antenna in order to make measurements of the effective zenith noise temperature. They measured a temperature which had a value of 3.5 ± 1 K higher than the expected temperature (Penzias and Wilson, 1965). This unexpected difference turned out to be the same in every direction on the sky and independent of seasonal variations. Therefore, the conclusion could be made that the signal was not arising from the Earth's atmosphere or our Milky Way; it had to be extragalactic (Penzias and Wilson, 1965). It was and is the cosmic microwave background radiation. In 1978 the scientists were rewarded with the Nobel Prize in Physics for this discovery.

Nowadays, we know that the temperature of the Cosmic Microwave Background, is not 3.5 K but 2.72548 ± 0.00057 K (Fixsen, 2009).

The Cosmic Microwave Background

The Cosmic Microwave Background (CMB) is a thermal isotropic radiation that is present in the entire Universe. It was created at the time of *recombination*. In this time, after being hot and dense, the Universe had been cooled down by the adiabatic expansion of the Big Bang. The temperature that was reached allowed protons and electrons to 'recombine' into hydrogen atoms. Due to this recombination, photons were released. These atoms were not able to absorb the thermal radiation any more and therefore finally the Universe became transparent to light. The photons could therefore travel freely though out space. As the photons travel, the universe expands causing the photons' wavelength to red shift. Therefore these photons correspond to a black body having a cooler temperature. Due to the red shifting, the photons measured today have a wavelength of about 1 mm, which corresponds to the microwave part of the spectrum. The CMB radiation contains important information regarding the field of Cosmology. The existence of the CMB is an important evidence for the 'Big Bang Model' (White, 1999).

The CMB has the shape of a thermal black body spectrum because the spectrum follows the Planck function, see equation (3.4), for a temperature of 2.726 K (Fixsen, 2009). Until today, it is the most perfect black body ever measured in nature (White, 1999).

Our radio telescope

This project is based on building a Radio Telescope in order to observe the CMB, the Sun and other possible sources. The project is implemented by four students, Bram Lap, Maik Zandvliet, Frits Sweijen and Willeke Mulder (myself). All four have an area of specialization, which they focus their thesis on. Bram Lap will be focussed on the designing and building of the Horn antenna (Lap, 2015), Maik Zandvliet will concern about the construction and the receiver Back-End of the telescope (Zandvliet, 2015) and Frits Sweijen will develop the software running the telescope and he will observe the Sun and other possible sources (Sweijen, 2015).

The main purpose of this thesis will be to determine the observational requirements, influencing the design and construction of the Pickett-Potter Horn antenna, develop a strategy to remove the contribution of the atmospheric emission, and to measure the CMB with the telescope.

The highest value for the brightness corresponds to the peak of the spectrum, located at a frequency of 175 GHz. It would be easiest to observe the CMB with this frequency. Unfortunately, this is not possible for our telescope. We had the limitations that we could use the existing leftover filters and amplifiers from SRON, corresponding to a frequency of 4 to 12 GHz. It seemed obvious to choose a higher frequency, because the brightness is higher at higher frequencies. Due to the range of our filter, we chose an observing frequency of 11 GHz, having a bandwidth of 1 GHz.

This thesis will concentrate on the calibration part of the observation, while taking into account the Earth's atmosphere. In Chapters 2 and 3 there will be a review of the 'basics' behind the Earth's atmosphere and its atmospheric opacity. Then more details will be given about measuring the CMB. Where after the design specifications of the telescope will be established in Chapter 4. To measure a useful temperature, we have to calibrate the telescope. Concerning the calibration, different aspects of the telescope have to be taken into account. This will be fully explained in the Chapters 5 and 6. In addition, the software to determine the temperature of the CMB according to the observational data will be developed. The Chapters 8 and 9 of the thesis contains the plots, conclusions and discussion from the observations.

2 | Atmospheric opacity

In order to observe the Universe, we have to be able to receive signals through the Earth's atmosphere. The atmosphere that effects radio waves can be divided into two layers, the troposphere and the ionosphere. The troposphere is the region just above the Earth's surface. The ionosphere is located from about 50 to 400 kilometres, containing many ions and free electrons.

The radio spectrum goes up to a frequency of 1 THz, but is limited by the ionosphere, which prevents radio waves of passing through the atmosphere below frequencies of 10 MHz. This is why for the use of ground-based radio telescopes, the Earth's atmosphere is of great importance. The atmosphere creates a window defining the frequency range for radiation in the electromagnetic spectrum that is able to reach the Earth's surface. However, having a dry atmosphere, e.g. without clouds, the refractive index for radio wavelengths is the same as for optical wavelengths (Burke and Graham-Smith, 2010).

In the field of radio astronomy, the Earth's atmosphere can be considered stable over a relatively long period. Still some aspects have to be taken into account considering radio observations. Atmospheric absorption depends on the altitude of the observing location above sea level, the elevation of the astronomical source and the transparency of the atmosphere, also called the opacity or optical depth.

2.1 Opacity

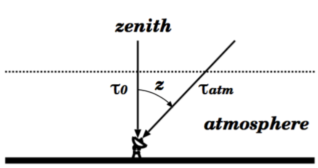


Figure 2.1: This figure illustrates the sec z dependence of the optical depth of the atmosphere τ_{atm} with the assumption of a flat atmosphere. *Credits: Sasao and Fletcher, 2009*

The opacity along the line of sight will change as a function of the zenith angle. Here the zenith angle is defined as the angle from the zenith to the horizon. *From now on in this thesis, each time an angle is mentioned it will be defined to be a zenith angle being 0° at the Zenith and 90° at the horizon.* According to Wilson et al. (2013), if the atmospheric physical parameters are assumed to be independent of position and only depend on the height in the atmosphere, the opacity can be written as

$$\tau(z) = \tau_0 \cdot X(z) \tag{2.1}$$

where τ_0 is the optical depth at the zenith and $X(z)$ is a function for the air mass. This function can be expressed as:

$$X(z) = \frac{1}{\int_0^\infty \rho(h)dh} \int_0^\infty \frac{\rho(h)}{\sqrt{1 - \left(\frac{R}{R+h}\frac{n_0}{n}\right)^2 \sin^2 z}} dh \tag{2.2}$$

In equation (2.2), R is defined as the radius of the Earth, ρ as the gas density in the atmosphere and n as the index of refraction.

According to Burke and Graham-Smith (2010), the atmospheric absorption is small and sometimes can even be neglected below an observing frequency of 10 GHz. In addition, clouds absorb and scatter radio waves at frequencies around 6 GHz and the strong water-vapor line is strongest around 22 GHz. As we have an antenna operating at 11 GHz, we can neglect these effects and are able to encounter an approximately stable atmosphere. Therefore, the values for the atmospheric temperature and the opacity will not change a lot during an observing time of several minutes. According to Sweijen (2015) the temperature can fluctuate a lot during several hours during the day, but taking into account that a measurement of the CMB will take a minute or two, these variations would not cause high fluctuations. This enables that by measuring a calibration source through different air masses, the value for the opacity can be determined, because we can assume a flat atmosphere. This simplifies the calculations considering the determination of the value for the opacity in Groningen. The expression for the airmass will be simply $X(z) = \sec z$ and therefore the equation for the opacity becomes

$$\tau_{\text{atm}} = \tau_0 \sec z. \tag{2.3}$$

A visual interpretation of this expression is shown in Figure 2.1.

Being able to work with equation (2.3) requires an accurate value of the optical depth at the zenith. The National Radio Astronomy Observatory has got available data from the Green Bank Telescope measuring the zenith opacity for different frequencies. Figure 2.2 shows the effects of water vapour for different frequencies. Here it becomes clear that having an observing frequency that is below ~ 22 GHz will imply suffering less from the effects of water vapour on the zenith opacity. However, we also want to observe at as high a frequency as possible to maximise the brightness of the CMB. This is why we chose to observe at 11 GHz. This choice of observing frequency was also set by considering the available equipment.

According to our supervisor, John McKean, we could estimate the zenith opacity in Groningen to be around a value of 0.05. This is a worst case scenario, but also still a good approximation taking into account the data from the Green Bank Telescope. The value for 11 GHz corresponds to a zenith opacity of around 0.01. As we are located in the Netherlands, being below sea level, the opacity will be a little higher. Thus, a zenith opacity of 0.05 as a worst case scenario is a good approximation. Therefore, in the following calculations and plots the value of $\tau_0 = 0.05$ is taken into account, starting with a clear visualization of how the opacity changes as a function of the zenith angle. As mentioned before, if a flat atmosphere is assumed, the atmospheric opacity follows a sec function. This can be concluded by looking at equation (2.3). At larger angles, the function goes to infinity and therefore is not valid. This is shown in Figure 2.3.

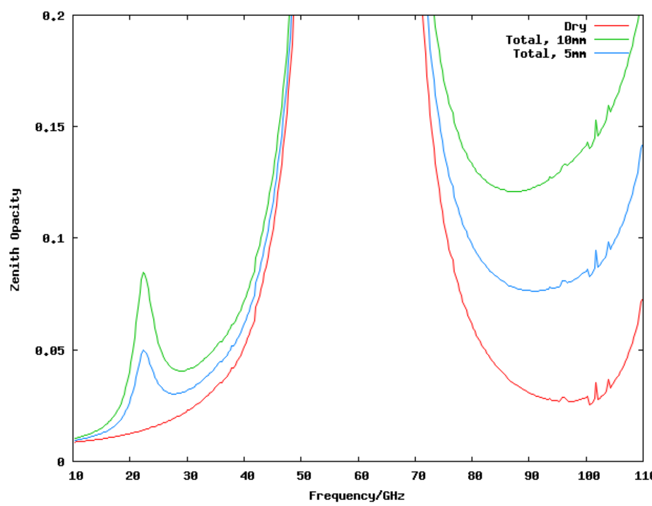


Figure 2.2: Atmospheric opacities at the zenith for a dry atmosphere, an atmosphere having 5 mm precipitable water vapor (pwv), and with 10 mm pwv. The values are valid for locations near the Green Bank site. *Credits: http://www.gb.nrao.edu/mustang/wx.shtml*

2.2 Fluctuations in the zenith opacity

The more obstacles, e.g. clouds and aerosols, radiation has to pass trough the atmosphere, the more opaque it becomes. This means that the zenith opacity is not a fixed value for every location and every time. In addition, the zenith opacity differs as a function of frequency. The Green Bank Telescope provides a forecast representing estimates of the current and estimated zenith opacity. These forecasts show its dependence on frequency and for different places, Elkins, Hotsprings, and Lewisburg. The opacities for these locations, which we will use as a guide are shown in Figure 2.4. Due of the fact that a low value is an advantage when doing observations with a radio telescope, predictions for the zenith opacity are made for three days. These get updated every day. An example for such a forecast is shown in Figure 2.4(b),(d).

From these plots we can clearly see that the value for the Zenith opacity can fluctuate a lot during the day. During the days in June, the highest value is about 0.03 while most of the time the zenith opacity is approximately 0.01. The forecast for July shows a larger fluctuation. Here the opacity peaks at values around 0.05 and the lowest value is approximately 0.015. For these figures the opacities are derived by using the Millimeter-Wave Propagation Model (MWP) of Liebe. This model describes various properties, such as attenuation, of moist air for frequencies up to 1000 GHz. (Liebe, 1985) They are based on the presence of resonance lines, three of H_2O and 40 from O_2, the continuum of H_2O and the dry air.

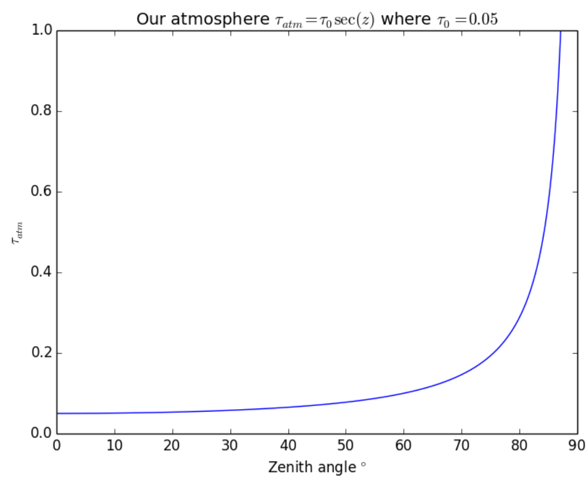


Figure 2.3: The zenith dependence of the atmospheric opacity is shown. At larger angles, the larger the distance travelled trough the atmosphere and therefore the value for the optical depth is higher.

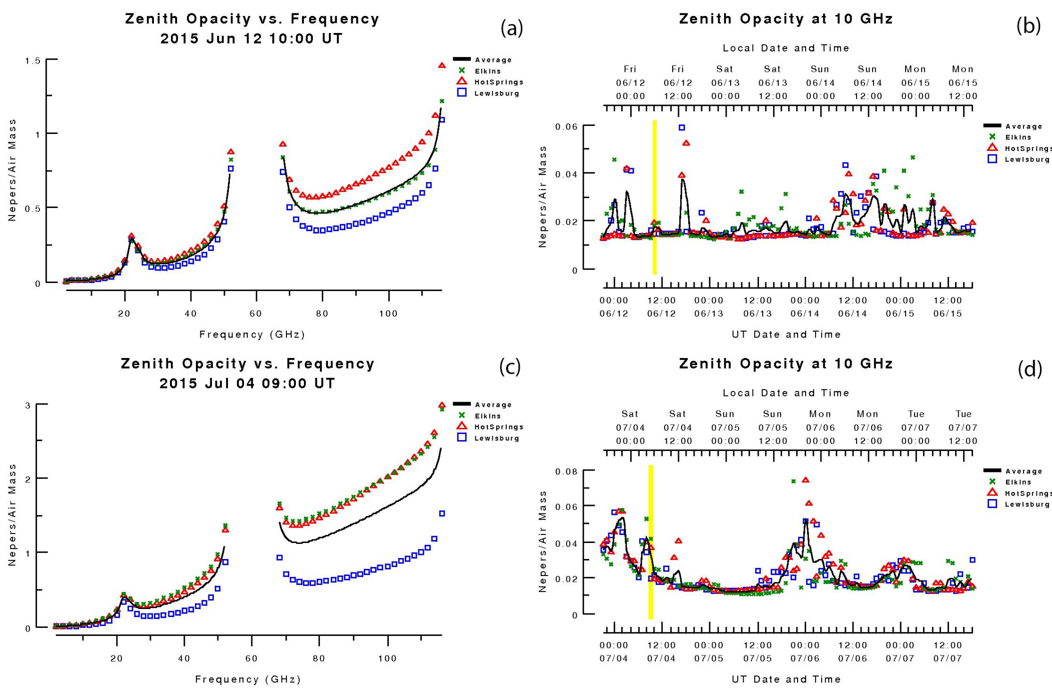


Figure 2.4: The High Frequency Weather Forecasts are shown. Made by Ronald J Maddalena on behalf of the National Radio Astronomy Observatory with the Green Bank Telescope. The plots show the 3.5-Day (NAM) Forecasts of the Zenith Opacity is calculated and plotted as function of observing frequency (a) and at 10 GHz (b) for the 12$^{\text{th}}$ of June 2015 at 10:00 UT. In addition, the Zenith Opacity as function of observing frequency (c) and at 10 GHz (d) for the 4$^{\text{th}}$ of July 2015 at 09:00 UT are shown. *Credits: http://www.gb.nrao.edu/∼rmaddale/WeatherNAM /opacity.html*

3 | Atmosphere above Groningen

Due to the fact that there is not any data available considering the sky and atmosphere above Groningen, I made a model in order to get an impression about how precise we have to measure the opacity of the sky. This model is based on a set of simulations and requires a good control of and knowledge about the equation of radiative transfer, which I first review in order to develop the necessary formalism. From the radiative transfer equation the expression describing the antenna and system temperature will be derived. These expressions will show the importance of the accuracy and stability of the zenith opacity in order to be able to measure the temperature of the CMB.

3.1 Radiative transfer

To understand the basics concerning the radiative transfer equation, I first will introduce the definitions of brightness, flux density and the brightness temperature. As we also want to understand the CMB's black body approximation, I will also explain the basics regarding Planck's Law.

3.1.1 Brightness and flux density

It is important to recognize the difference between brightness and flux density. When we measure radiation, we measure the amount of photons falling on a detector. When taking into account a specific observing solid angle, this number of photons is independent of distance. This is also known as the brightness. When we are considering the whole sky, the number of photons does decrease with increasing distance. This is called the apparent flux (Wilson et al., 2013) .

Brightness

In radio astronomy, we often use the term brightness instead of specific intensity. The specific intensity I_ν can be defined by the quantities ϑ, $\mathrm{d}\sigma$ and $\mathrm{d}\Omega$. Here ϑ describes the angle between the normal vector of the receiver and the incoming radiation, $\mathrm{d}\sigma$ the surface area of the receiver and $\mathrm{d}\Omega$ the measured solid angle on the sky. The intensity is related to the energy E passing a surface area per unit time t, per unit frequency $(\nu, \nu + \mathrm{d}\nu)$ by, $\mathrm{d}E = I_\nu \cos\vartheta \mathrm{d}\sigma \mathrm{d}\Omega \mathrm{d}t \mathrm{d}\nu$. Since the power is defined to be the energy per unit time, the power can be expressed as

$$\mathrm{d}P = I_\nu \cos\vartheta \mathrm{d}\sigma \mathrm{d}\Omega \mathrm{d}\nu. \tag{3.1}$$

Rewriting equation (3.1), the expression for the specific intensity becomes,

$$I_\nu = \frac{\mathrm{d}P}{\cos\vartheta \mathrm{d}\sigma \mathrm{d}\Omega \mathrm{d}\nu}. \tag{3.2}$$

Flux density

Radio telescopes usually measure the flux density, S_ν, of a source. Considering a discrete radio source, the flux density equals the specific intensity integrated over a solid angle on the sky $\mathrm{d}\Omega$,

$$S_\nu = \int_{\Omega_s} I_\nu(\vartheta, \phi) \cos(\vartheta) \mathrm{d}\Omega. \tag{3.3}$$

This flux density is the radiation power collected per unit frequency and area. It is defined by the specific intensity and therefore characterised by the astronomical source itself. The powers measured from sources in the Universe are small and will cause small values for the specific intensity. Eventually, these will lead to fluxes in the order of 10^{-20} to 10^{-30} W m^{-2} Hz^{-1}. To measure these fluxes, the unit Jansky is introduced. One Jansky (= 1 Jy) is equal to 1×10^{-26} W Hz^{-1} m^{-2}.

3.1.2 Planck 's law and brightness temperature

To fully understand the concept behind radiation, it is important to know the definition of a black body. A black body is an object having the ability to absorb radiant energy at all frequencies. After all available energy is absorbed, the black body will reach an equilibrium where eventually the body will emit all energy at the same time as it was absorbed. The shape of the black body intensity spectrum depends on the temperature.

Planck 's law

The *Planck law* describes the distribution of the intensity of electromagnetic radiation radiated by a black body as a function of frequency. It states that

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}, \tag{3.4}$$

where h is the Planck constant ($= 6.62 \times 10^{-34}$ J s), c is the speed of light (= 299,792,458 m s^{-1}), ν is the frequency, T is the temperature and k is the Boltzmann constant ($= 1.3806488 \times 10^{-23}$ m^2 kg s^{-2} K^{-1}).

The peak of the Planck function is a characteristic of different temperatures. As the temperature is increasing, the peak will show a higher brightness and lower frequencies. The shift of the peak is explained though the *Wien's displacement Law*. The maxima's are found by using $\partial B_\nu / \partial \nu = 0$,

$$\left(\frac{\nu_{\mathrm{max}}}{\mathrm{GHz}}\right) = 58.789 \left(\frac{\mathrm{T}}{\mathrm{K}}\right). \tag{3.5}$$

Using this expression for the peak of the Planck function, it can be determined that for the CMB, $T = 2.73$ K, the peak of the CMB brightness is at a frequency of 160.23 GHz.

If $x = h\nu/kT$ is far from the maximum, the Planck Function can be simplified. There can be made a distinction between the two limiting cases $x \gg h\nu/kT$ and $x \ll h\nu/kT$ (Wilson et al., 2013).

1. Having $x \gg h\nu/kT$ the exponential $e^{h\nu/kT} - 1$ dominates the Planck function. Therefore the expression will become

$$B_W(\nu, T) \approx \frac{2h\nu^3}{c^2} e^{-h\nu/kT}. \tag{3.6}$$

   This limit is called *Wien's Law.*

2. Having $x \ll h\nu/kT$ the exponential $e^{h\nu/kT} - 1$ can be expanded using Taylor expansion to $e^{h\nu/kT} - 1 \cong \frac{h\nu}{kT}$. Therefore the expression will become

$$B_{RJ}(\nu, T) \approx \frac{2\nu^2}{c^2} kT. \tag{3.7}$$

   This limit is called the *Rayleigh-Jeans Law.* This approximation for the Planck Law is most relevant to the radio observations that we will make. It demonstrates that observing at as high a frequency as possible is important which can be inferred from $B(\nu, T) \propto \nu^2$.

Brightness temperature

In order to have a practical way of measuring a received intensity, we use the term and definition *brightness temperature.* It is defined to be the temperature that a black body should have in order to emit the received intensity. Therefore, it is an apparent temperature and not the physical temperature of the source. Being in the low-frequency regime, we can take into account the Rayleigh-Jeans Law (see equation (3.7)). This causes B_ν to be directly proportional to the temperature.
Often, the specific intensity is also defined in terms of the brightness temperature. Due to the fact that the brightness temperature is defined by $I_\nu = B_\nu(T_B)$ for a black body, the expression for the specific intensity of the CMB becomes

$$I_\nu = \frac{2\nu^2}{c^2} kT_B. \tag{3.8}$$

3.1.3 The radiative transfer equation

Now I have mentioned the basic definitions, I will elaborate the radiative transfer equation. According to Wilson et al. (2013), radiative transfer can be described as a mechanism of transporting energy in the form of electromagnetic radiation. In free space, photons simply do not encounter or interact with any obstacles. Therefore, the specific intensity I_ν of radiation remains independent of distance along a path s, meaning $\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = 0$. But, in a medium I_ν can change due to the emission or absorption of radiation. These gains and losses can be expressed through the adsorption, κ_ν, and emission, ϵ_ν coefficient.

Together, the interaction between radiation and matter are described by the *equation of radiative transfer*, stating

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\kappa_\nu I_\nu + \epsilon_\nu. \tag{3.9}$$

There are a couple of limiting cases where the radiative transfer equation has got a simple solution. The solutions for thermodynamic equilibrium (TE) and local thermodynamic equilibrium (LTE) will be relevant for this thesis.

1. **Thermodynamic equilibrium**. A system being in mechanical chemical and thermal equilibrium is in thermodynamic equilibrium, meaning the intensity within the source does not change with distance, ds. In this limiting case, the specific intensity can be described by the Planck function, depending on the temperature. Having $\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = 0$, equation (3.9) can be written as

   $$I_\nu = B_\nu(T) = \epsilon_\nu/\kappa_\nu.$$

   This solution is known as *Kirchhoff's law.*

2. **Local thermodynamic equilibrium**. Local thermodynamic equilibrium implies independent degrees of freedom in the system to be in equilibrium over time. Therefore, we can describe a volume of air as having a specific temperature and pressure. In order to write the solution for the radiative transfer equation in this equilibrium, we use the optical depth, τ_ν. This is an important term when making observations with a ground based telescope. Describing the optical thickness and being dimensionless, the optical depth can be defined by

   $$\tau_\nu(s) = \int_{s_0}^{s} -\kappa_\nu(s)\mathrm{d}s. \tag{3.10}$$

   Together with Kirchoff's law, the equation of radiative transfer can be written as

   $$-\frac{1}{\kappa_\nu}\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = \frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = I_\nu - B_\nu(T). \tag{3.11}$$

   The solution is determined through multiplying equation (3.11) with the exponent $e^{-\tau_\nu(s)}$

   $$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu}e^{-\tau_\nu(s)} = (I_\nu - B_\nu(T))\, e^{-\tau_\nu(s)}.$$

Integrating over τ_ν from zero to $\tau_\nu(s)$ will give the following,

$$I_\nu(s)e^{-\tau_\nu(s)}\Big|_0^s + \int_0^{\tau(s)} I_\nu e^{-\tau_\nu(s)}\mathrm{d}\tau_\nu - \int_0^{\tau(s)} I_\nu e^{-\tau_\nu(s)}\mathrm{d}\tau_\nu = I_\nu(s)e^{-\tau_\nu(s)} - I_\nu(0)e^{-\tau_\nu(0)}.$$

Under the assumption that $\tau_{\nu(0)} = 0$, being isothermal the temperature stays constant for every value of τ and s. Therefore, if T, $T(\tau)$, $T(s)$ is constant, the solution of equation (3.9) can be written as

$$I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + B_\nu(T)\left(1 - e^{-\tau_\nu(s)}\right) \tag{3.12}$$

For radio astronomy, we often apply the Rayleigh-Jeans Law. This is allowed because we are are located in the limiting regime of $h\nu \ll kT$. From equation (3.7) it becomes clear that the brightness temperature is proportional to the dynamic temperature when considering a black body emitting electro magnetic radiation. Therefore, in the centimetre wavelength regime, equation (3.9) can be written as,

$$\frac{\mathrm{d}T_b(s)}{\mathrm{d}\tau_\nu} = T_b(s) - T(s), \tag{3.13}$$

where $T_b(s)$ and $T(s)$ respectively represent the brightness temperature and the thermodynamic temperature of the medium, at location s. Through the same calculations used in the limiting case for LTE, the solution will become

$$T_b(s) = T_b(0)e^{-\tau_\nu(s)} + \int_0^{\tau_\nu(s)} T(s)e^{-\tau}\mathrm{d}\tau. \tag{3.14}$$

Being isothermal, we can write equation (3.14) as,

$$T_b(s) = T_b(0)e^{-\tau_\nu(s)} + T(s)(1 - e^{-\tau_\nu(s)}). \tag{3.15}$$

This expression for $T_b(s)$ is also known as the antenna temperature.

3.2 Antenna temperature

To explain the definition of an antenna temperature, we consider a receiving antenna. Aiming at a certain point in the sky, the antenna has got the normalized power pattern $P_n(\vartheta, \varphi)$. At this point the brightness distribution is $B_\nu(\vartheta, \varphi)$. This distribution induces a power at the antenna output. In this situation, the total power in the antenna, $\mathscr{P}_\nu$, equals

$$\mathscr{P}_\nu = \frac{1}{2}A_e \iint B_\nu(\vartheta, \varphi)P_n(\vartheta, \varphi)\ \mathrm{d}\Omega, \tag{3.16}$$

per unit bandwidth, ν, where A_e is the effective aperture. With the use of the Rayleigh-Jeans approximation and the Nyquist theorem, the antenna temperature, T_A, can be defined to be $\mathscr{P}_\nu = kT_A$. Substituting equation (3.16) gives the following expression for the antenna temperature;

$$T_A = \frac{1}{2k} A_e \iint B_\nu(\vartheta, \varphi) P_n(\vartheta, \varphi)\ \mathrm{d}\Omega. \tag{3.17}$$

By using the beam solid angle instead of the effective aperture, equation (3.16) becomes

$$\boxed{T_A(\vartheta_0, \varphi_0) = \frac{\int T_B(\vartheta, \varphi) P_n(\vartheta - \vartheta_0, \varphi - \varphi_0) \sin\vartheta\ \mathrm{d}\vartheta\ \mathrm{d}\varphi}{\int P_n(\vartheta, \varphi)\ \mathrm{d}\Omega}}. \tag{3.18}$$

Another definition for the antenna temperature can be expressed by rewriting equation (3.15). Measuring the CMB allows us to define $T_B(s = 0) = T_{\mathrm{cmb}}$, $T(s) = T_{\mathrm{atm}}$ and as mentioned before, $T_b(s)$ equals the antenna temperature T_A. Therefore, we get the expression,

$$T_A = T_{\mathrm{cmb}} e^{-\tau(s)} + T_{\mathrm{atm}}(1 - e^{-\tau(s)}). \tag{3.19}$$

This is the equation we must solve in order to determine the temperature of the CMB.

3.2.1 Dependence of the zenith opacity on the antenna temperature

If not mentioned otherwise, the simulations and information expanded in the coming sections is based on the assumptions that the atmospheric temperature $T_{atm} = 283$ K and the zenith opacity $\tau_0 = 0.05$.

The combination of equation (3.19) and equation (2.3), shows the importance of the accuracy of the value for the zenith opacity. During observations, measurements need to be carried out as accurate as possible. Simulations show that a small uncertainty in the value for the zenith opacity already implies larger changes in the antenna temperature T_A, which is shown in Figure 3.1. At larger angles, the uncertainties will cause larger fluctuations in the antenna temperature than for smaller angles.

To find out more about the temperature fluctuation caused due to a changing value of the zenith opacity, Figure 3.2 is made.

The plots show that being off by a value of 0.01, 0.005 or 0.001 in τ_0 can cause antenna temperature fluctuations of ∼30 K, ∼14 K and ∼4 K respectively. This shows the importance of doing a quick observation. A fluctuation in τ_0 causes large fluctuation in the received antenna temperature.

3.3 Uncertainty calculations for the zenith opacity

Our main goal in the building the radio telescope is to measure the CMB. The cold CMB having a temperature of 2.73 K, makes it difficult to distinguish the contribution from the

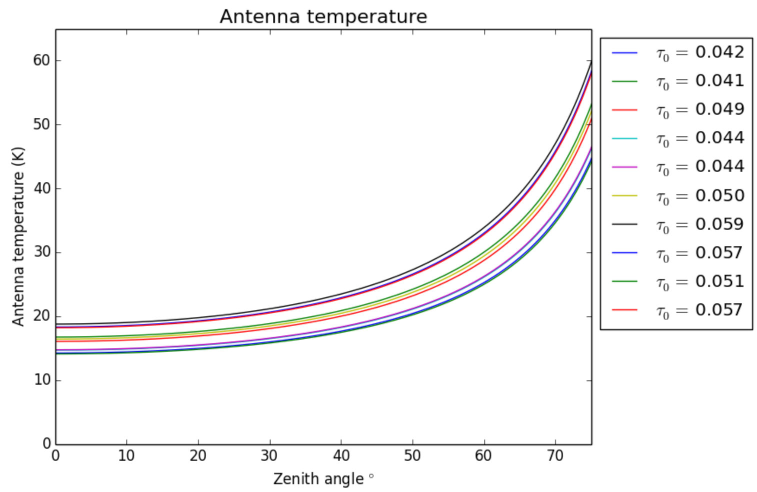


Figure 3.1: The plot shows a simulation of the dependence of the zenith opacity value to the antenna temperature.

CMB and the contribution of the atmosphere to the antenna temperature. The ultimate goal is to achieve an uncertainty of a maximum of 10 percent in the CMB temperature measurement. Via the use of propagation of uncertainties, the local thermodynamic equilibrium solution of the radiative transfer equation makes it possible to investigate what should be our maximum uncertainty in the value for the opacity in order to achieve this precision.

A way of determining the maximum allowed uncertainty in the measurement to obtain the value for the zenith opacity τ_0 is by the use of the Exact Formula of Propagation of Error, see equation (A.6). Here f stands for the expression of the zenith opacity extracted from the equation of the system temperature, which will be described in the following section.

3.4 System temperature

Having a whole system, the antenna temperature but also the receiving part of the antenna adds uncertainties that have to be taken into account. The system temperature is a combined temperature, which depends on the antenna and the receiver temperature, $T_{\text{sys}} = T_A + T_{\text{receiver}}$. The antenna temperature includes T_{ground}, which will be discussed in Section 5.2.2. In this section the ground temperature contribution is neglected. Again, the antenna temperature T_A is given by equation (3.19). The receiver temperature T_{rx} can be determined by performing measurements and calculations, which is elaborated in Section 5.1.2. Together the expression for the system temperature becomes,

$$T_{\text{sys}} = T_{\text{cmb}} e^{-\tau_\nu(s)} + T_{\text{atm}}(1 - e^{-\tau_\nu(s)}) + T_{\text{rx}}. \tag{3.20}$$

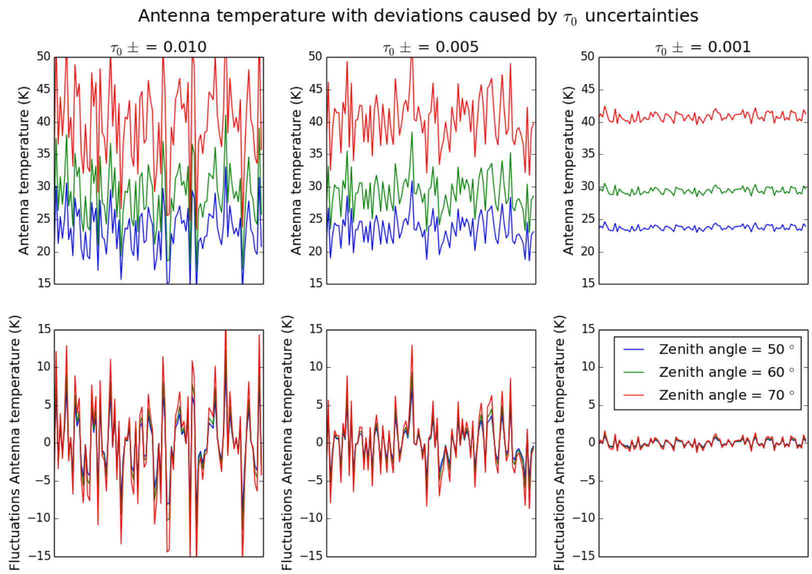


Figure 3.2: In this plot are 100 measurements simulated having random errors for the value of τ_0. They vary between the first, second and third column with the uncertainty of 0.01, 0.005 and 0.001, respectively. In the upper plots the fluctuations in the antenna temperature are shown for different fixed angles, blue is 50°, green is 60° and red is 70°. The lower plots show scaled fluctuations.

In this case $\tau(s)$ again depends on the zenith angle by $\tau(s) = \tau_0 \sec z$. Therefore we can rewrite the expression to

$$T_{\text{sys}} = T_{\text{cmb}} e^{-\tau_0 \sec z} + T_{\text{atm}}(1 - e^{-\tau_0 \sec z}) + T_{\text{rx}}. \tag{3.21}$$

We want to know how precise we need to measure the zenith opacity in order to measure the CMB. Therefore τ_0 is extracted from equation (3.21),

$$\tau_0 = -\ln\left(\frac{T_{\text{sys}} - T_{\text{rx}} - T_{\text{atm}}}{T_{\text{cmb}} - T_{\text{atm}}}\right)\left(\frac{1}{\sec z}\right). \tag{3.22}$$

Due to the fact that we want to measure the CMB temperature of 2.73 K with an uncertainty of 10 percent, the error in T_{sys} can have a maximum value of 0.273 K.

Exact formula for propagation of error

$$\sigma_{\tau_0} = \sqrt{\left(\frac{\partial\tau_0}{\partial T_{\text{sys}}}\right)^2 \sigma^2_{T_{\text{sys}}} + \left(\frac{\partial\tau_0}{\partial T_{cmb}}\right)^2 \sigma^2_{T_{cmb}} + \left(\frac{\partial\tau_0}{\partial T_{atm}}\right)^2 \sigma^2_{T_{atm}} + \left(\frac{\partial\tau_0}{\partial T_{rx}}\right)^2 \sigma^2_{T_{rx}}} \tag{3.23}$$

Using equation (3.22), we are able to calculate the derivatives of τ_0 with respect to all the components, T_{sys}, T_{cmb}, T_{atm}, T_{rx}:

$$\left(\frac{\partial \tau_0}{\partial T_{sys}}\right) = \frac{\partial}{\partial T_{sys}}\left[-\ln\left(\frac{T_{\rm sys}-T_{\rm rx}-T_{\rm atm}}{T_{\rm cmb}-T_{\rm atm}}\right)\left(\frac{1}{\sec z}\right)\right] = \frac{1}{T_{\rm atm}+T_{\rm rx}-T_{\rm sys}}$$
$$\left(\frac{\partial \tau_0}{\partial T_{\rm cmb}}\right) = \frac{\partial}{\partial T_{\rm cmb}}\left[-\ln\left(\frac{T_{\rm sys}-T_{\rm rx}-T_{\rm atm}}{T_{\rm cmb}-T_{\rm atm}}\right)\left(\frac{1}{\sec z}\right)\right] = \frac{1}{T_{\rm cmb}-T_{\rm atm}}$$
$$\left(\frac{\partial \tau_0}{\partial T_{atm}}\right) = \frac{\partial}{\partial T_{atm}}\left[-\ln\left(\frac{T_{\rm sys}-T_{\rm rx}-T_{\rm atm}}{T_{\rm cmb}-T_{\rm atm}}\right)\left(\frac{1}{\sec z}\right)\right] = \frac{T_{\rm cmb}+T_{\rm rx}-T_{\rm sys}}{(T_{\rm atm}+T_{\rm cmb})(T_{\rm atm}+T_{\rm rx}-T_{\rm sys})}$$
$$\left(\frac{\partial \tau_0}{\partial T_{rx}}\right) = \frac{\partial}{\partial T_{rx}}\left[-\ln\left(\frac{T_{\rm sys}-T_{\rm rx}-T_{\rm atm}}{T_{\rm cmb}-T_{\rm atm}}\right)\left(\frac{1}{\sec z}\right)\right] = \frac{1}{(T_{\rm sys}-T_{\rm atm}-T_{\rm rx})}$$

Applying propagation of errors to τ_0, while taking into account the whole telescope system, requires some values for the uncertainties. The expected uncertainty due to the sensitivity of the used temperature sensor depends on the temperature itself by $\sigma_{T_{atm}} = 0.6 + 0.005 \times (T_{\rm atm} - 273.15)$ K. We want to achieve $\sigma_{T_{cmb}} = 0.273$ K and therefore $\sigma_{T_{\rm sys}} = 0.273$ K. Regarding the receiver, I assume the values $T_{\rm rx} = 200$ K and $\sigma_{T_{rx}} = 1$ K. Looking at equation (3.23) shows that there is not a dependence on τ_0 itself. Therefore the value for τ_0 does not matter in this calculation.

Plotting σ_{τ_0} as a function of the zenith angle z, gives the plot shown in Figure 3.3. From this plot we can conclude that we need an uncertainty which can have a maximum value of $\sim$0.0075 at the zenith. Since we plan to make measurements until 70° we have to take into account an uncertainty of $\sim$ 0.0025.

Measurement uncertainties

Until now, I only discussed uncertainties to set constraints for the designing and building of the telescope. However, these uncertainties are not the only ones that we have to take into account. During observations we have to take into account that we will encounter measurement uncertainties. The largest uncertainty is coming from the power meter (see Sweijen, 2015 for more information about the power meter). To be able to correct as much as possible for the measurement uncertainties, we have to observe every angle of the sky a couple of times and integrate over all values. From statistics we know that measuring N times will reduce the measurement uncertainty with $1/\sqrt{N}$. To calculate the uncertainty in our received power, which is being converted to $T_{\rm sys}$, we apply propagation of error to equation (3.21). Therefore the expression to be solved becomes,

$$\sigma_{T_{\rm sys}} = \sqrt{\left(\frac{\partial T_{\rm sys}}{\partial T_{\rm cmb}}\right)^2 \sigma^2_{T_{\rm cmb}} + \left(\frac{\partial T_{\rm sys}}{\partial T_{\rm atm}}\right)^2 \sigma^2_{T_{\rm atm}} + \left(\frac{\partial T_{\rm sys}}{\partial T_{\rm rx}}\right)^2 \sigma^2_{T_{\rm rx}} + \left(\frac{\partial T_{\rm sys}}{\partial \tau_0}\right)^2 \sigma^2_{\tau_0}}. \quad (3.24)$$

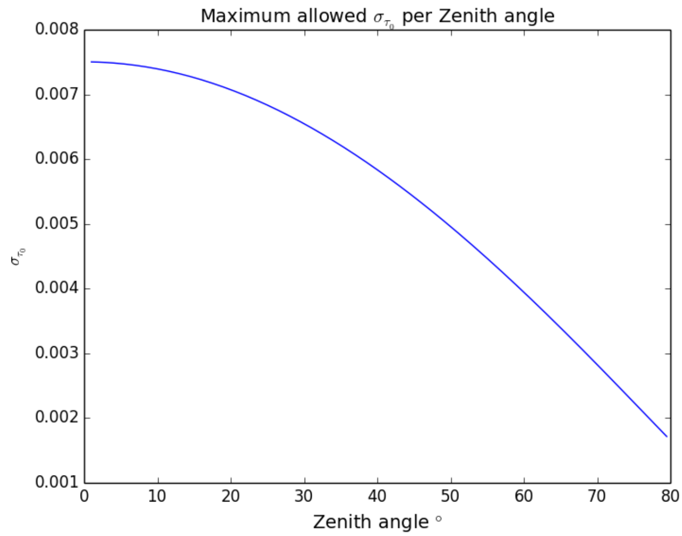


Figure 3.3: The uncertainty allowed in the value for τ_0, in order to be able to measure the temperature of the CMB with 10 percent accuracy. This plot takes into account the whole system of the telescope.

Using equation (3.21), we are able to calculate the derivatives of all the components, T_{cmb}, T_{atm}, T_{rx}, τ_0, with respect to T_{sys}:

$$\left(\frac{\partial T_{\text{sys}}}{\partial T_{\text{cmb}}}\right) = \frac{\partial}{\partial T_{\text{cmb}}}\left(T_{\text{cmb}}e^{-\tau_0 \sec z} + T_{atm}(1 - e^{-\tau_0 \sec z}) + T_{\text{rx}}\right) = e^{-\tau_0 \sec z}$$
$$\left(\frac{\partial T_{\text{sys}}}{\partial T_{\text{atm}}}\right) = \frac{\partial}{\partial T_{\text{atm}}}\left(T_{\text{cmb}}e^{-\tau_0 \sec z} + T_{\text{atm}}(1 - e^{-\tau_0 \sec z}) + T_{\text{rx}}\right) = (1 - e^{-\tau_0 \sec z})$$
$$\left(\frac{\partial T_{\text{sys}}}{\partial T_{\text{rx}}}\right) = \frac{\partial}{\partial T_{\text{rx}}}\left(T_{\text{cmb}}e^{-\tau_0 \sec z} + T_{\text{atm}}(1 - e^{-\tau_0 \sec z}) + T_{\text{rx}}\right) = 1$$
$$\left(\frac{\partial T_{\text{sys}}}{\partial \tau_0}\right) = \frac{\partial}{\partial \tau_0}\left(T_{\text{cmb}}e^{-\tau_0 \sec z} + T_{\text{atm}}(1 - e^{-\tau_0 \sec z}) + T_{\text{rx}}\right) = e^{\tau_0 \sec z} \sec z(T_{\text{atm}} - T_{\text{cmb}}).$$

The exact calculations for the uncertainties will be carried out after an observation using equation (3.24). There is a simplification of equation (3.21) for the optically thin regime ($\tau \ll 1$), where $e^{-\tau_0 \sec z} \approx (1 - \tau_0 \sec z)$. This results in

$$T_{\text{sys}} = T_{\text{cmb}} + (T_{\text{atm}} - T_{\text{cmb}})\tau_0 \sec z + T_{\text{rx}}. \tag{3.25}$$

4 Establishing the telescope design specifications

The designing of the telescope depends on the available equipment, but in order build a specific horn antenna to measure the CMB, we have to establish some design specifications. These specifications are obtained by investigating the influence of the antenna beam. The first section will clarify the fundamentals of the antenna beam on the received power pattern and main beam solid angle. Thereafter, I set the requirements for the size of the main beam and the minimum values for the side-lobes

4.1 The antenna beam

The power pattern

In the field of designing antennas, the power pattern is an often used term. It describes the directional and angular dependence of the relative distribution of the measured radiation power. Looking at the case of a transmitting isotropic antenna; if a spectral power [1] (W Hz^{-1}) is fed into the antenna, it would transmit the same power per solid angle. Therefore the power, $P(\vartheta, \varphi)$, is the power per solid angle per unit bandwidth (W Ω^{-1} Hz^{-1}). Therefore, the total power at a fixed frequency, ν, is $4\pi P_\nu$. The 4π is arising from an integration over the whole sky.

According to Collin (1985), the *directivity* of an antenna describes the ratio of the radiated power to the average radiated power. This is comparable to the emission of an isotropic antenna. The *directive gain* of an antenna is about the same as the directivity, except that the directive gain takes into account the incoming power instead of the total radiated power. Therefore, the directive gain can be defined to be

$$G(\vartheta, \varphi) = 4\pi \frac{\text{power radiated per unit solid angle}}{\text{input power}} = \frac{4\pi P(\vartheta, \varphi)}{\iint_{4\pi} P(\vartheta, \varphi) \mathrm{d}\Omega}. \tag{4.1}$$

Usually, the power pattern measured is the *normalized power pattern*, P_n. This is the ratio of the power pattern over the maximum power,

$$P_n(\vartheta, \varphi) = \frac{P(\vartheta, \varphi)}{P_{\max}} = \frac{G(\vartheta, \varphi)}{G_{\max}}. \tag{4.2}$$

[1] Spectral power equals, $P_\nu = kT$, where T is temperature and k is the Boltzmann constant.

The (main) beam solid angle

The beam solid angle of an antenna is a parameter used to describe the solid angle on the sky, sampled by the antenna beam. This angle is defined by

$$\Omega_A = \iint_{4\pi} P_n(\vartheta, \varphi)\ \mathrm{d}\Omega = \int_0^{2\pi} \int_0^{\pi} P_n(\vartheta, \varphi) \sin\vartheta\ \mathrm{d}\vartheta\ \mathrm{d}\varphi. \tag{4.3}$$

In the case of an isotropic antenna, the whole power pattern is equal to the maximum of the power pattern. Therefore, from equation (4.2) it can be concluded that for an isotropic antenna the normalized power pattern P_n is 1 for all Ω_A. Unfortunately, this ideal antenna does not exist. Instead as a function of position on the sky, most antennas have smaller values for the normalized power pattern. Still for a certain range of ϑ and φ, the normalized power pattern has the largest value. This range is called the *main beam solid angle*, also known as the main lobe. Therefore, the mean beam solid angle is defined to be

$$\Omega_{MB} = \iint_{\text{main lobe}} P_n(\vartheta, \varphi)\ \mathrm{d}\Omega. \tag{4.4}$$

To describe the efficiency of the antenna, the term *main beam efficiency* is introduced. It is defined to be the ratio of the main lobe and the total beam solid angle. It is described by,

$$\eta_B \equiv \frac{\Omega_{\mathrm{MB}}}{\Omega_{\mathrm{A}}}. \tag{4.5}$$

Besides the main lobe, there are also areas outside the principle response that are non-zero. These areas are called *side-lobes*. As the side-lobes can add a lot to the total power pattern, it is important to take into account the additional signal received in the side-lobes of an antenna when astrophysical measurements are being done. In the case of our telescope, the antenna has been designed in such a way to limit the total power received in the side-lobes (see Lap, 2015).

4.2 Determining a suitable beam size

In order to determine the value for the atmospheric opacity and the temperature of the CMB from our observations, a certain number of measurements is needed. However, pointing an antenna in one angular direction, will not provide a measurement of the received power in that particular direction only. Due to the power pattern of our antenna, having a main beam and side-lobes, measuring at a certain angle will take into account signals from other directions. We have minimised the side-lobe level to -40 dB (see Lap, 2015). This required side-lobe level is discussed in Section 4.3 However, we must also determine the size of the main lobe. In order to correct for the atmosphere, we measure the sky in fixed angular steps and integrate over the angle range. The size of this step will define the size of the horn itself. For example, if we want to measure steps of ten degrees, the main beam of the horn has to be less than this. Therefore, this is an important factor for determining the size of the horn.

4.2.1 Number of measurements needed

Having an error in a determined value can change the whole interpretation of a measurement. For example, this simulation is based on equation (3.15). To show how important accuracy of a measurement can be, I add an uncertainty of ± 5 K to the antenna temperature. This causes already a larger region of the parameter space where a function can get plotted through. As we want to determine the cold temperature of the CMB, we want to know how many angles we have to take into account in order to achieve an accurate value for τ_0.

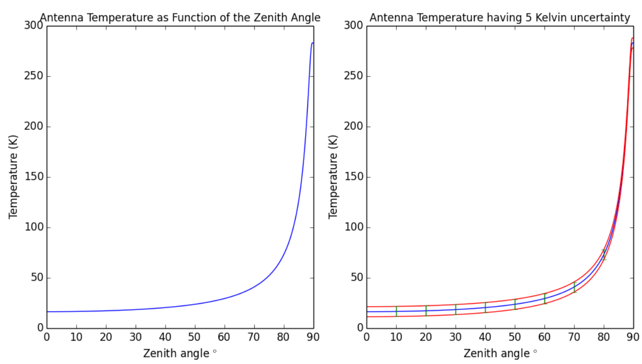


Figure 4.1: The left plot shows a visual interpretation of $T_A = T_{\text{cmb}} e^{-\tau_0 \sec z} + T_{\text{atm}}(1 - e^{-\tau_0 \sec z})$. The right plot shows $\sigma_{T_A} = 5$ K, which gives an impression about which values T_A can reach having an uncertainty.

According to the stability of the atmospheric opacity per zenith angle, we can describe the stability, to check whether it is enough to have e.g. four measurements in order to reach an accuracy of 10 percent for the CMB temperature. To test this, simulations are carried out. The simulations are divided into two parts. The first part is to check how many measurements we need to determine the value for the opacity that is precise enough. The second part is to check at how many angles we have to measure, before being able to measure the CMB. During the following simulations, the assumption of $T_{\text{atm}} = 283$ K is made. The simulations are based on the scripts shown in Appendix B and C

Measurements needed to measure the zenith opacity τ_0

1. In order to be able to measure the CMB, our biggest concern and difficulty is measuring the value for the zenith opacity as accurate as possible. To determine

how many measurements are preferable in order to measure the CMB, we start with the definition of the antenna temperature, $T_A = T_{\text{cmb}} e^{-\tau_0 \sec z} + T_{\text{atm}}(1 - e^{-\tau_0 \sec z})$. First, I simulate a normal distribution to create random errors for τ_0 with the python function *numpy.random.normal*. Here I use the value $\tau_0 = 0.05$ as our μ and four different values for the σ. Plotting T_A with the use of the uncertainties in τ_0 results in the plots shown in Figure (4.2). Note that to be able to plot this function, the temperature for the CMB is already known and used.

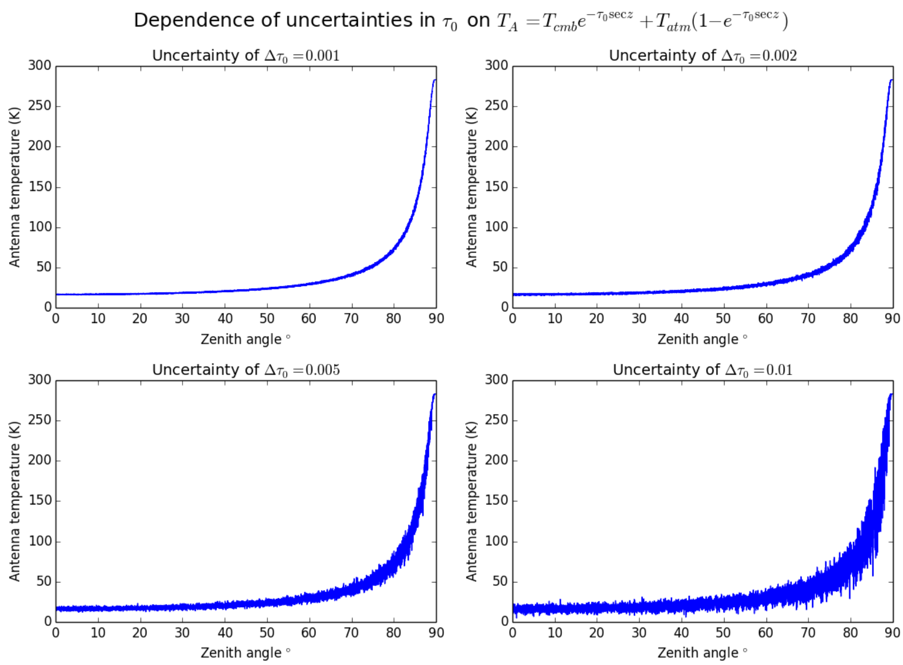


Figure 4.2: Four plots are shown presenting T_A for an observation sweep of the sky. Applying different errors for the value of τ_0 results in the bubbly distribution. The simulations are based on a normal distribution of uncertainties. The angles are plotted from 0° to 90° in 9000 steps.

These plots already show that having an uncertainty of 0.005 can result in a temperature uncertainty of more than 2 K. Therefore the next step is looking how many times we have to measure the sky in order to reach a precision of τ_0 that results in a temperature uncertainty of less than ∼2 K.

2. With the use of the script shown in Appendix B, I simulated a range of measurements of the sky, integrating over each value and then checked how quickly we can measure the opacity. We already know that we are going to measure a received power on every angle of the sky in order to determine the zenith opacity. Therefore I take step sizes of 1°. My program simulates every measurement for different values of the uncertainty in τ_0 and therefore looks like a real observation.

3. Running the simulation results in the values shown in Table 4.1. Due to the fact

Measurements	$\Delta\tau_0 = 0.001$	$\Delta\tau_0 = 0.002$	$\Delta\tau_0 = 0.005$	$\Delta\tau_0 = 0.01$
1	0.04789	0.04979	0.05143	0.05281
5	0.04986	0.04973	0.05067	0.04996
10	0.04965	0.04995	0.04992	0.05063
50	0.04983	0.04998	0.04975	0.04942
100	0.05011	0.04999	0.04987	0.04934
500	0.04992	0.04998	0.04981	0.04951

Table 4.1: One example of my simulated data. The numbers represent the value for the zenith opacity. This allows me to check how many measurements of the sky are needed in order to be able to determine an accurate value for the zenith opacity τ_0.

that the values are generated randomly every time that I run the simulation other values are shown. Therefore, I can not conclude hard results, only that I know that doing more measurements on every angle on the sky increases the accuracy of the measurement. Knowing that the value of τ_0 is 0.05 seems promising. Doing one measurement would be unwise, but is possible. Doing a hundred observations per angle will give us a very good precision. Therefore, the constraint is being made that the power meter has to be able to read out data quick enough to measure one angle on the sky as many times as possible within a second or so.

Measurements needed to measure T_{cmb}

During the previous simulation T_{cmb} was known and we wanted to fit a function in order to obtain the zenith opacity τ_0. Now I am going to do that simulation the other way around. By fixing the value for τ_0, I will be able to fit a function in order to obtain a temperature for the CMB. Same as the previous simulation, the equation for the antenna temperature T_A is used.

1. First, again I plot the values for the T_A for every zenith angle. Using the same uncertainties as done by the previous simulation, the plot shows exactly the same. Now I fix τ_0 when taking into consideration that τ_0 has got uncertainties. Using *scipy.plot.optimize* I am able to fit for the simulated data. All temperatures are mentioned in Table 4.2.

2. In Table 4.2 the blue marked data represents the simulated temperatures falling inside our requirement concerning the T_{cmb}. From this it can be inferred that measuring the opacity as good as possible is indeed of importance, but being to able to make more measurements of the sky is even more important.

From the values presented in Table 4.1 and 4.2 it becomes clear that already two observations are enough to measure τ_0 as accurate to determine T_{cmb} within 10 percent.

Measurements	Samples	$\Delta\tau_0 = 0.001$	$\Delta\tau_0 = 0.002$	$\Delta\tau_0 = 0.005$	$\Delta\tau_0 = 0.01$
1	sample2	2.3120 K	1.6458 K	0.8834 K	4.8253 K
	sample5	2.7640 K	2.2552 K	0.1815 K	8.0604 K
	sample10	2.7550 K	2.6646 K	4.5931 K	3.2293 K
5	sample2	2.9303 K	2.3511 K	3.3210 K	1.6164 K
	sample5	2.8014 K	2.3807 K	3.0514 K	3.0427 K
	sample10	2.7391 K	2.7487 K	2.1482 K	3.5850 K
10	sample2	2.7725 K	2.7599 K	2.5297 K	1.1023 K
	sample5	2.7191 K	2.7194 K	2.7661 K	3.8094 K
	sample10	2.7430 K	2.7377 K	2.7069 K	2.1324 K
50	sample2	2.7047 K	2.5285 K	2.9365 K	2.5683 K
	sample5	2.7712 K	2.7148 K	2.6530 K	2.5892 K
	sample10	2.7835 K	2.7497 K	2.7191 K	2.7220 K
100	sample2	2.7279 K	2.7994 K	2.8004 K	2.6549 K
	sample5	2.6667 K	2.6633 K	2.9252 K	2.7904 K
	sample10	2.7256 K	2.7400 K	2.6152 K	2.5549 K
500	sample2	2.7088 K	2.7415 K	2.8273 K	2.7801 K
	sample5	2.7295 K	2.7389 K	2.7364 K	2.7677 K
	sample10	2.7167 K	2.7300 K	2.7031 K	2.5519 K

Table 4.2: One example of my simulated data. The numbers represent the value for the measured T_{cmb}. The T_{cmb} having an accuracy of 10 percent or less are marked blue. This allows me to check how many measurements of the sky and how many samples are needed in order to be able to determine an accurate value for the temperature of the CMB. There are three different samples being used; sample2 are two measurements of T_A at 22° and 67°, sample5 are five measurements of T_A at 15°, 30°, 45°, 60° and 75° and sample10 are ten measurements of T_A at 7°, 15°, 22°, 30°, 37°, 45°, 52°, 60°, 67° and 75°.

Note that this is only a simulation and therefore a theoretical interpretation. During a real observation we have to take into account the system temperature instead of the antenna temperature, which adds a value for the receiver temperature. Also the ground can contribute to the signal coming in to the system. The contribution coming from the ground is discussed in Section 5.2.2. During a measurement of the opacity we ideally measure a sky without other sources, e.g. the Sun and Geostationary Satellites, because we want a clear sky with only signals arising from the atmosphere and CMB. In addition, we know that our system is not perfect. Therefore, we also need to take the uncertainty in the system into account.

Looking at the simulations above, we can infer that in order to measure the temperature of the CMB, we have to be at least able to get two measurement points and therefore at least a sample of 5 observations in the range from 0° till $\sim 70°$. Therefore, an antenna full width at half maximum of $< 14°$ is needed.

4.2.2 Stability of the atmospheric equations

To attain a favourable value for the opacity, the whole sky has to be taken into account. Measuring the system temperature on every zenith angle would be preferable but to determine the amount of measurements we look how fast equation (2.3) changes with the zenith angle. As we will integrate over a range of angles, this change will be presented for different angle step sizes. This is done by dividing the values for the angles, going from 0° to 90° in steps of 10°, 20°, 30° and 40°. The values for τ_{atm} are subtracted from the average τ_{atm} value for every step. The results are shown in Figure 4.3. Basically, we search for the plot that follows the equation the best. We only want to measure the Zenith angle range from 0° till $\sim 70°$, because the 10° and the 20° step sizes seem usable. In Figure 4.4 the same script is applied, only for equation (3.15) to see how the antenna temperature changes.

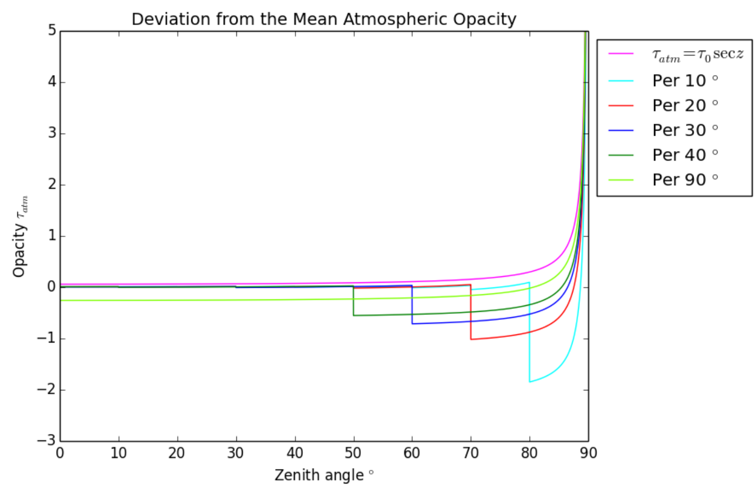


Figure 4.3: The change of the atmospheric opacity is plotted against the zenith angle. From this simulation becomes clear that having a beam of 10°-20° you will be able to measure every 10° till 20°, which makes it able to avoid the exponential, coming from the ground and horizon, as long as possible.

My simulations show that having a horn with an angular size of the main beam between 10° and 20°, and with measurements the zenith angle until $\sim 70°$, we provide at least four measurements, as been found above, to determine the value for the CMB temperature.

4.3 Determining a suitable value for the side-lobes

As mentioned in the previous section, it is very important to take into account the beam during a measurement of the sky. The beam also contains side-lobes, which also measure

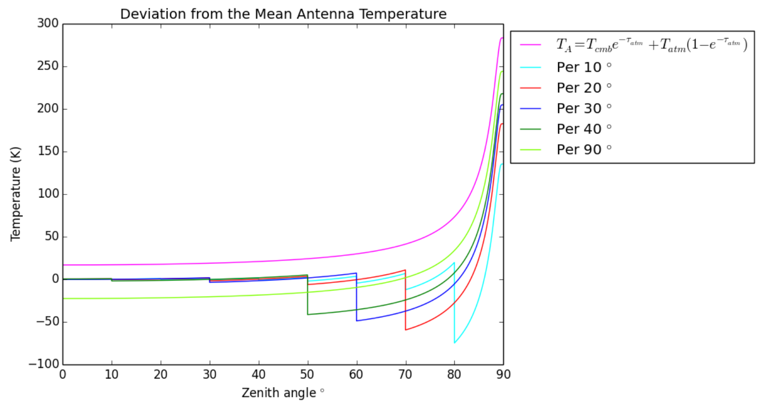


Figure 4.4: The same is plotted as in Figure4.3, but now for T_{ant}. From this we get the same conclusion that having a beam of 10°-20° you will be able to measure every 10° till 20°, which makes it able to avoid the exponential, coming from the ground and horizon, as long as possible.

power from other directions. This is particularly important as the power received from the ground could strongly contribute to the antenna temperature. Looking at different types of horn antenna designs, it becomes clear that every specific shape has got different values representing the first side-lobe levels, for example see Figure 4.5. In order to know which shape is most ideal for measuring the CMB, some design constraints have to be set.

At every angle, θ, the power pattern adds an amount of decibels to the total power. Most of the contribution is coming from the main lobe but there is also a contribution from the side-lobes. Therefore the side-lobe levels must have a certain value, in order to obtain an accuracy of 0.1 K. Let's assume the background contribution of the ground falling into the whole beam is 300 K. Having an accuracy of 0.1 K implies that a temperature of less than 0.1 K is not added within the side-lobes. This can be determined though the calculation of the allowed contribution of the temperature according to the background temperature. By the use of the Nyquist formula and the definition of Decibel, see equation (5.6), we can relate the temperature to a power, thus the allowable gain for a 300 K ground temperature is

$$\text{Gain} = 10 \times \log_{10}\left(\frac{0.1\text{K}}{300\text{K}}\right) = -34.77 \text{ dB}.$$

From the calculations it becomes clear that the first side-lobe levels must have at least a value of ~ -35 dB. Also discussed by Lap (2015) concerning different horn shapes, see Figure 4.6, a circular horn has a first side-lobe levels of ~ -17 dB, a rectangular horn ~ -13 dB and the Pickett-Potter horn ~ -40 dB. Therefore, it becomes clear that in order to measure a contribution of 0.1 K from spurious off-axis sources like the ground at 300 K, only the Pickett-Potter horn antenna meets the requirements.

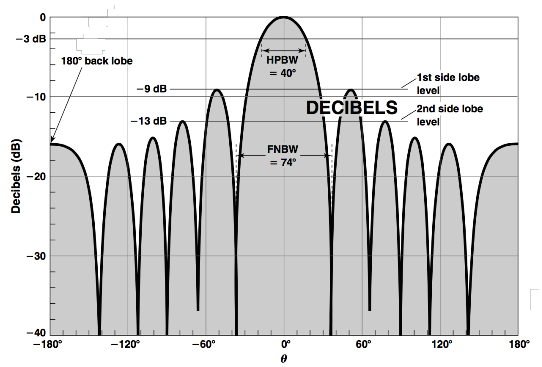


Figure 4.5: The entire beam of an antenna exists of one main beam, defining the half power beam width, and side-lobes. The most important are the first side-lobe levels, because they contribute the most of all side-lobes to the total receiving power. *Credits: Sasao and Fletcher, 2009*

Testing the final horn after construction found one axis of the antenna beam to have a side-lobe level of -20 dB. For a ground temperature of 300 K, this would result in a contribution of 3 K to the system temperature, which would make measuring the 2.73 K temperature of the CMB challenging. For this reason, it was decided to rotate the horn in a way that the -20 dB side-lobe level was perpendicular to the direction of the ground. The side-lobe level in the direction of the ground was found to be -40 dB, which was well within the design requirement that I determined.

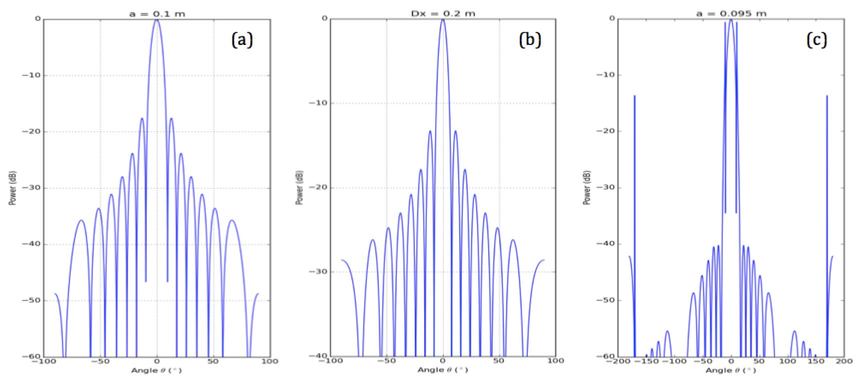


Figure 4.6: The plots above show the simulations of the power pattern for different shapes for horn antennas. (a) Circular Horn Antenna, (b) Rectangular Horn Antenna, (c) Pickett-Potter Horn Antenna. *Credits: Lap, 2015*

5 Calibration of the telescope

To be able to measure the zenith opacity of the sky and afterwards the temperature of the CMB, it is crucial to relate the incoming radio signals, measured in mW, to a system temperature. Then equation (3.21) can be used to fit the data for τ_0 and $T_{\rm cmb}$.

5.1 Hot-cold load observation

In order to make calibrated observations of the sky with the radio telescope, we need to perform a hot-cold load observation. By applying this method we can determine the values of the receiver noise temperature, the sky temperature and the optical depth. After applying this method, we are able to set the calibration scale factors and therefore convert our power measurements to the temperature scale. Note that the power measured is not directly related to the observed temperature because of the use of amplifiers in the telescope back-end (see Zandvliet, 2015).

5.1.1 The method

Beams having cold and hot loads will give different power due to the different observed temperature. The change in the power is measured using a power meter (see Sweijen, 2015). The hot load could be the ambient temperature. This ambient temperature is measured by the use of an absorber. Below an observing frequency of 230 GHz, we are able to use liquid nitrogen for the cold load.

5.1.2 Y-factor and receiver temperature

The receiver noise temperature is defined by a function called the Y-factor, which is given by

$$Y = \frac{V_{hot}}{V_{cold}} = \frac{P_{\rm hot}(\rm W)}{P_{\rm cold}(\rm W)}, \tag{5.1}$$

where V and P are the voltages and powers measured, respectively. Having a receiver, the outputs given for the hot and the cold loads are related to the receiver gain $G(v)$ through

$$\begin{aligned} V_{\rm hot} &= (P_{\rm hot} + P_{\rm rx})G, \text{ and} \\ V_{\rm cold} &= (P_{\rm cold} + P_{\rm rx})G. \end{aligned} \tag{5.2}$$

The expression and definition of the gain is elaborated in Section 5.1.3. This gives an equation for the receiver temperature:

$$T_{\rm rx} = \frac{P_{\rm hot} - P_{\rm cold}Y}{Y - 1}. \tag{5.3}$$

5.1.3 Gain

One of the definitions of the *gain* is already mentioned in Section 4.1. It is important to distinguish the definitions for antenna gain and amplifier gain. Amplifiers, as opposed to antennas, do have a power source. Therefore the amplifier gain gets the definition

$$G(\text{mW}) = \frac{P_{hot}(\text{mW}) - P_{cold}(\text{mW})}{k\Delta\nu(T_{hot} - T_{cold})}, \tag{5.4}$$

where k is the Boltzmann constant and $\Delta\nu$ the observation bandwidth of the telescope.

Decibels

Amplifiers are electronic devices with the ability to increase the magnitude of an incoming power or signal. Using these devices, a small received signal from the sky can be amplified into a measurable signal. Due to the fact that the gain describes a ratio of powers. On the logarithmic scale it can be described by the unit *decibel gain* (dB). As we work with powers, we will use the expression for *Power gain*, which is given by

$$G_P(dB) = 10\log_{10}\left(\frac{\text{P}_{\text{out}}(\text{W})}{\text{P}_{\text{in}}(\text{W})}\right). \tag{5.5}$$

As we will work with small signals, we will measure mW. Therefore the unit for the power gain will be dBm instead of dB. Powers can also be converted from mW to dBm and vice versa though:

$$\begin{aligned} P_{(\text{dBm})} &= 10 \cdot \log_{10}\left(\frac{P_{(\text{mW})}}{1\text{mW}}\right) \\ P_{(\text{mW})} &= 1\text{mW} \cdot 10^{\left(\frac{P_{(\text{dBm})}}{10}\right)}. \end{aligned} \tag{5.6}$$

5.2 The power pattern of our telescope

Making measurements of the sky involves taking into account the power pattern of the telescope. According to Section 3.2 and equation (3.18), measuring an antenna temperature of the sky will depend on the normalized power pattern $P_n(\vartheta, \varphi)$ of the telescope. Therefore, the powers coming out of the telescope will be the signals from the sky convolved with the power pattern.

5.2.1 Resolution

In order to gain more knowledge about the resolution of the telescope, we have to know the value for the HPBW of the power pattern. This can be achieved by the determination of the far field power pattern of the telescope, which can be examined in two ways.

1. Measuring a source in the near field of the telescope and using Fourier transformations in order to obtain the far field response of the telescope.

2. Measuring a point source in the far field of the telescope. This could be done using observations of the Sun (see Sweijen, 2015).

In this section the power pattern measured by Lap (2015) is used. He applied the method of measuring a source in the near field of the telescope. For more information about the measurements itself, see Lap (2015).

According to Lap (2015), measurements of the power pattern show that the telescope has got a half power beam width of 12.78° and 10.20° on the z- and y-axis respectively. Furthermore, the side-lobes are located around the -40 dB and -20 dB respectively, see Figure 5.1.

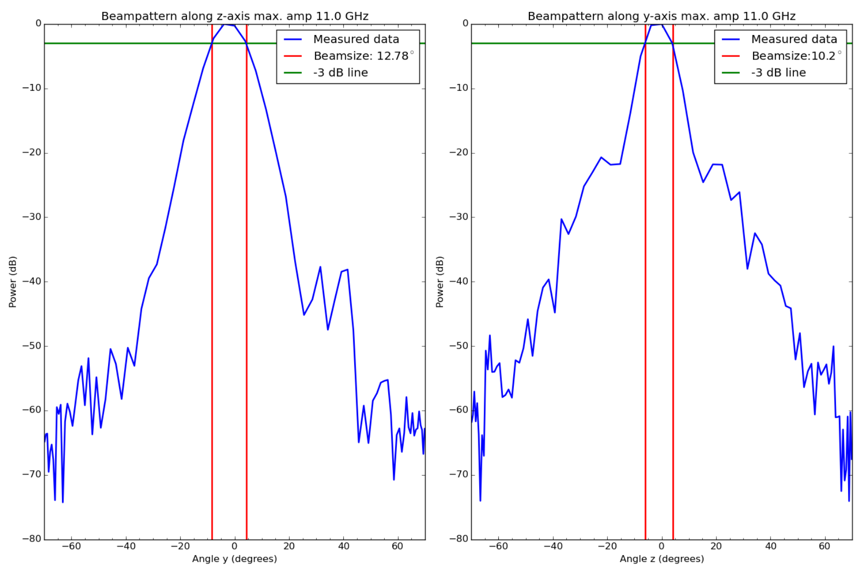


Figure 5.1: Shown in this plot are the far field power patterns, being a crosscut from the points where the maximal amplitude is reached for both y- and z-axis. For more details see Lap (2015)

5.2.2 Importance of the power pattern

Looking at the results from Lap (2015), we have a relatively large main beam, and small side-lobes. Here large and small refer to a main beam of 12.78° and side-lobes of -40 dB. Even though, the side-lobes are small, moving the telescope towards higher angles could have a large impact on the measurements of the antenna temperature, T_A. The equation for the antenna temperature, see equation (3.15), including the secant function, show high values for the temperature on higher angles. Therefore, even a small side-lobe can cause large temperature impacts. To check how much the power pattern contributes to the incoming signal, a simulation can be used. The simulation will reproduce a plot for the antenna temperature convoluted with the beam pattern.

Sky simulations including the beam response

I start with equation (3.15) representing the antenna temperature. In previous plots, the temperature equations were plotted for the zenith angle in the range 0° till 90°. As we have to convolve every angle in that range with a beam having a size of 139°, we have to increase the range of available angles. This can be done by reflecting the equation in the zenith. Figure 5.2 gives an impression of how the antenna temperature would look like, when taking into account the whole sky.

In order to be able to convolve the simulated sky signal with the measured beam pattern, the zenith angles, z, in the range from 0° till 90°, have to multiplied by the beam pattern having a total angular range of 139°, defined to be from -69° till 69°. Here the top of the main beam is located at 0°. The beam pattern along the z-axis, shown in Figure 5.1, shows an unexpected peak at the $+40°$. Since the peak is only shown on one side of the pattern, it is likely not a side-lobe. Therefore, it is probably a reflection, due to bad screening. In order to correct for the reflection when the near-field beam was being measured, the beam simulation is cut off in the range $-37 < \text{Angle y}(°) < 37$.

The simulation will multiply the beam by the sky signal by looping over every angle of the antenna temperature data. If we want to take into account the horizon, $z = 90°$, the data has to be extended by at least 37° because we can not multiply the beam without data.

There is still one practical problem with multiplying the simulation of the sky with the data of the beam pattern. The simulation of the sky is done in zenith angle steps of 1° The beam pattern is measured in 81 steps, extending over 139 °. In order to fit the beam pattern for every angle in the range $-37 < \text{Angle y}(°) < 37$, interpolation is used. This is represented in Figure 5.3. Here the blue lines represent the measured beam pattern data, and the red line a second order fit to the data. Now the fit can extract every value for the beam pattern at every angle.

As the signal of the sky will end at $z = 90°$, we can add a signal coming from the ground. Assuming the temperature added by the ground equals the temperature of the atmosphere, we can simulate the signal coming from the ground. This simulation is based on setting the values from the sky $(-90° < z < 90°)$ to $T = 0$ K, and outside this range the values from the ground to $T_{\text{ground}} = 293$ K. This fit for the ground is shown in Figure 5.4.

Now, knowing we have to take into account the ground when measuring near the horizon, a simulation is carried out on how the signals coming from T_{A} and T_{sys} behave when taking into account a T_{ground} of 293 K at the horizon. The convolved temperature signals are shown in Figure 5.5 and 5.6 for T_{A} and T_{sys} respectively.

No need to de-convolve our beam's power pattern from sky observations

Convolving a beam power pattern is easy, but de-convolving a power pattern from a sky power signal will require a lot of time, due to the methods of Fourier transforming, Fourier shifting, integrating, etc. Therefore, it would be great if we are able to correct for the ground by just not measuring the ground. Looking at Figure 5.5 and 5.6, we see that if we are able to do our observations until a zenith angle of about 80°, we do not measure a significant temperature contribution from the ground. This makes sense when looking at the side-lobe positions and levels. The side-lobes having a power level of -40 dB are able to pick up a signal of,

$$Gain = 10 \times \log_{10}\left(\frac{x}{T_{\text{ground}}}\right) = -40 \text{ dB}. \tag{5.7}$$

With T_{ground} being 293 K, the formula can be solved for x which gives $x = 0.0293$ K. Therefore a side lobe of -40 dB will cause an increase of temperature of ∼0.03 K. Using the same formula I can create a plot of how the gain looks like when using the values for T_{ground}. from Figure 5.4 as x and from thereon calculate the associated gain. This result in the plot on the right in Figure 5.4.

From the plot it becomes clear that the side lobes of the beam are already contributing at a zenith angle of 60°. This seems reasonable since we have a large beam extending over a range of ∼ 76°. Although the side-lobes occur at an angle of 60°, they still do not contribute a lot to the temperature signal coming from the ground. Therefore, if we want to correct for the ground contribution, we could simply not measure at angles higher than 80°. By doing that, we know for sure that we will not suffer from the contributions coming from the ground.

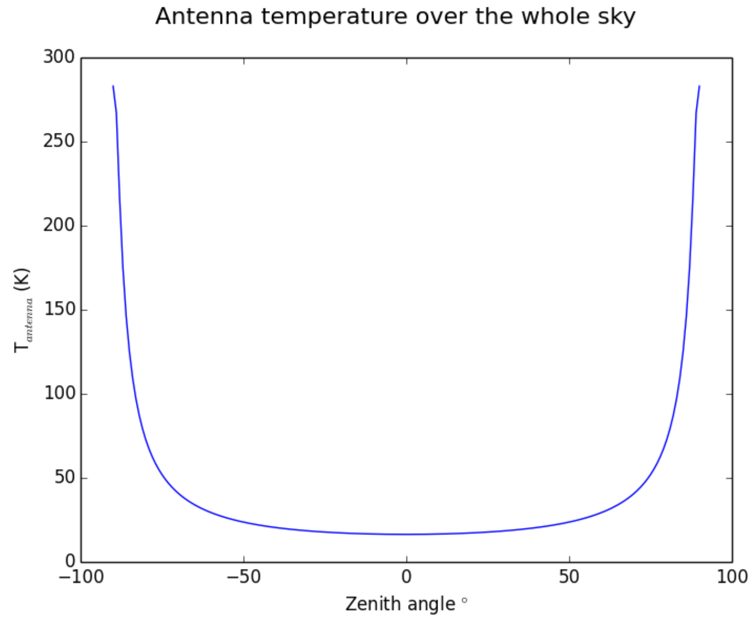


Figure 5.2: A simulation of the antenna temperature from the horizon, to the zenith and back to the horizon.

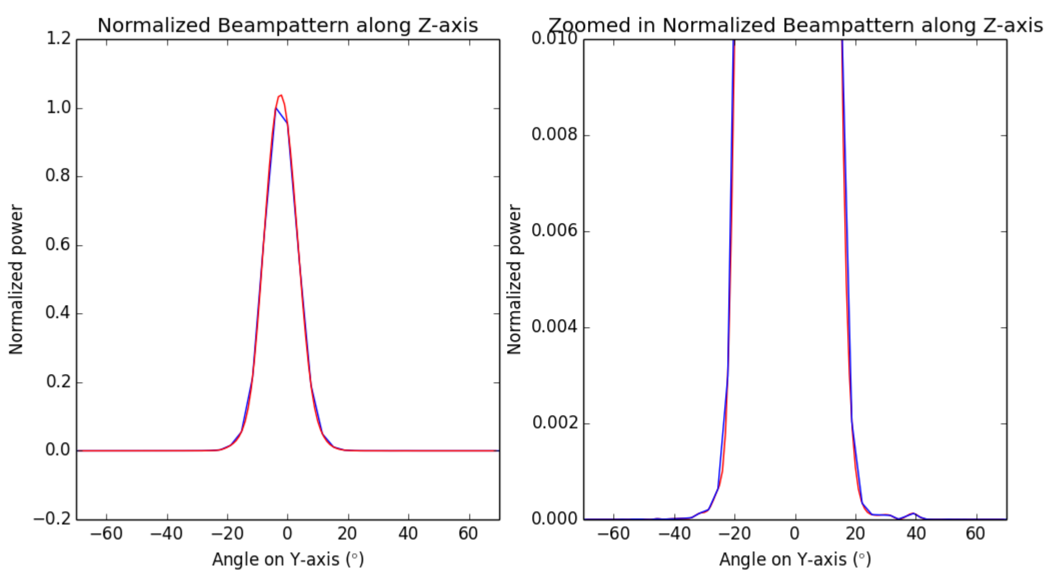


Figure 5.3: On the left, the beam pattern from the telescope is plotted. Shown in blue is the data of the beam pattern, measured by Lap (2015), and in red the fit achieved by interpolating done by myself. Due to the fact that Lap (2015) used 81 measurement points in order to measure the entire beam pattern, I make use of interpolation to get the values at each degree. I do this because I want to convolve every angle on the sky with the beam. On the right you see a zoom in to see how accurate the fit is.

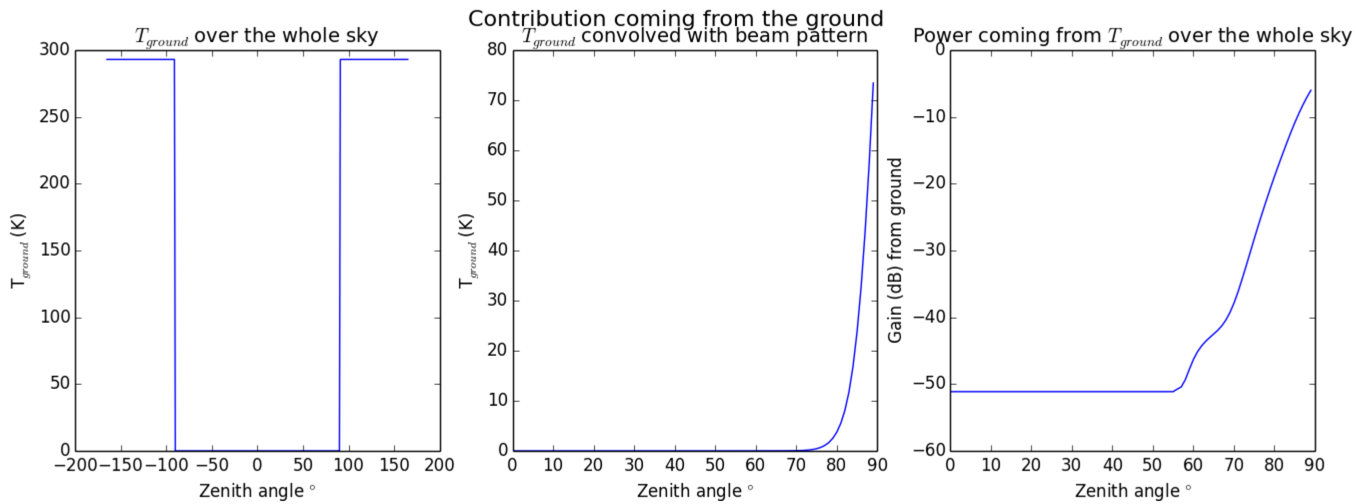


Figure 5.4: On the left temperature of the ground is simulated to have a value of T_{ground}=293 K. I assume the ground temperature to be 0 from horizon to horizon, referring to the angles from $-90° < z < 90°$. In the middle the left part of the left plot is convolved with the beam pattern measured by Lap (2015). On the right a simulation is shown which illustrates the behaviour of the gain if looking to the received signal of T_{ground}

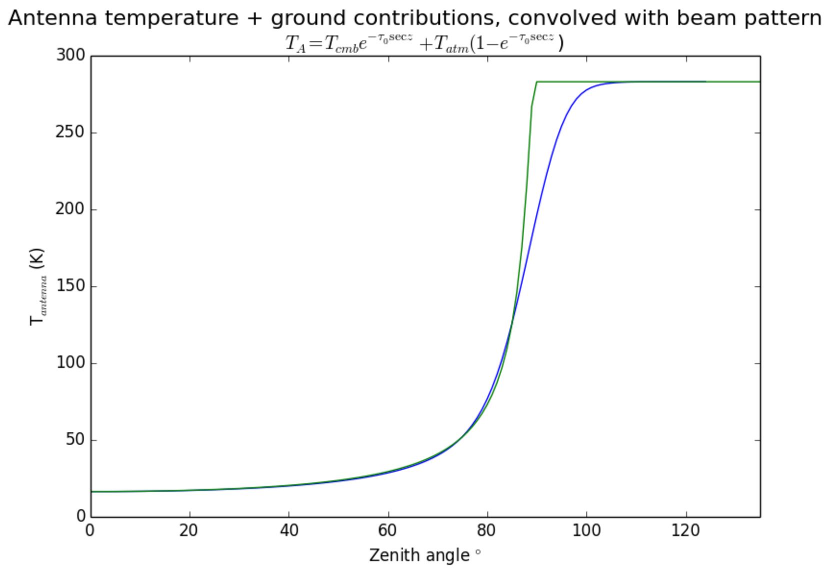


Figure 5.5: A simulation of the behaviour of T_A when taking into account the contribution coming from the ground.

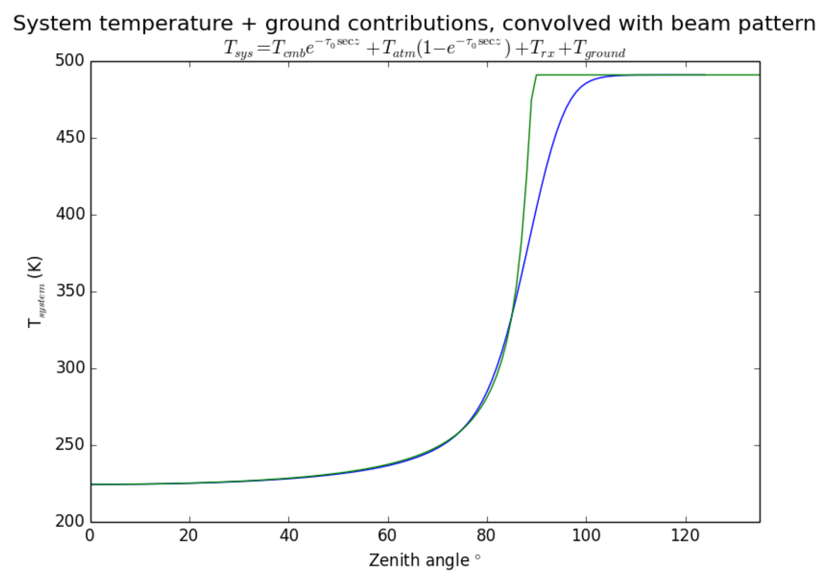


Figure 5.6: A simulation of the behaviour of T_{sys} when taking into account the contribution coming from the ground.

6 | Calibration done by observations

During the hot and cold load measurements of the system inside our office in the Kapteyn building, Zandvliet (2015) made a first estimate of the value for the receiver noise temperature. After I had done the first calibrated observations of the sky (see Appendix K), I plotted the received powers in dBm per angle on the sky. Two of these observations are shown in Figure 6.1 and 6.2. All plots showing T_{sys} per angle are made using the script shown in Appendix E.

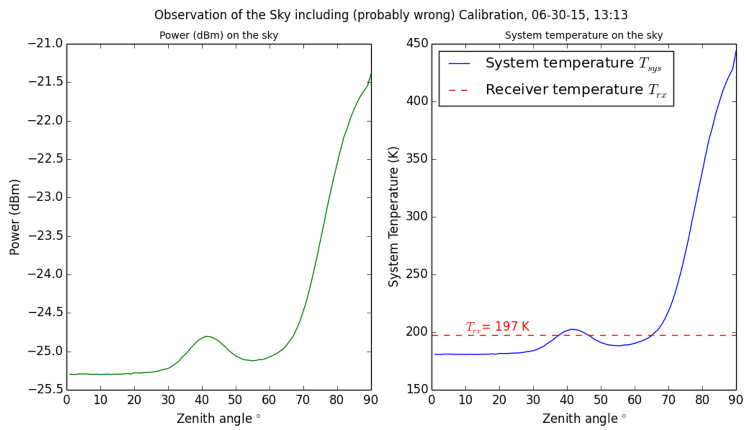


Figure 6.1: Observation made on 06-30-15 at 13:13. The received power show a contradiction to the formula for the system temperature. The system temperature is at the angles of $0° <$ Zenith angle $< 36°$ and $49° <$ Zenith angle $< 78°$ lower than the receiver noise temperature. This observation measured the powers: $P_{\text{cold}} = -23.4783$ dBm, $P_{\text{hot}} = -20.8990$ dBm and $P_{\text{Zenith}} = -25.2974$ dBm.

During the calibration the assumptions were made that $T_{\text{hot}} = 300$ K, $T_{\text{cold}} = 77.15$ K and $T_{\text{atm}} = 302$ K. The numbers are assumptions because we were not able to use the thermometers yet. The assumptions allow me to calculate a Y-factor (see equation 5.1), the receiver temperature T_{rx} (see equation 5.3), the gain (see equation 5.4) of the system and therefore the measured system temperature T_{sys} per angle on the sky. The system temperature T_{sys} turned out to be lower than the estimated value for the receiver noise temperature T_{rx}. As we know that $T_{\text{sys}} = T_{\text{sky}} + T_{\text{rx}} + T_{\text{ground}}$, it is not possible to have a higher receiver noise temperature than system temperature. This statement is in contradiction with the observations and calibration done.

There are various explanations for the T_{rx} begin higher than the T_{sys}. The high T_{rx} could be due to; the telescope measuring the hot and cold load powers wrong, a fault in the software of system itself, our atmospheric and hot load temperature estimations being off, a calculation error being made, or the beam is not entirely being filled by the

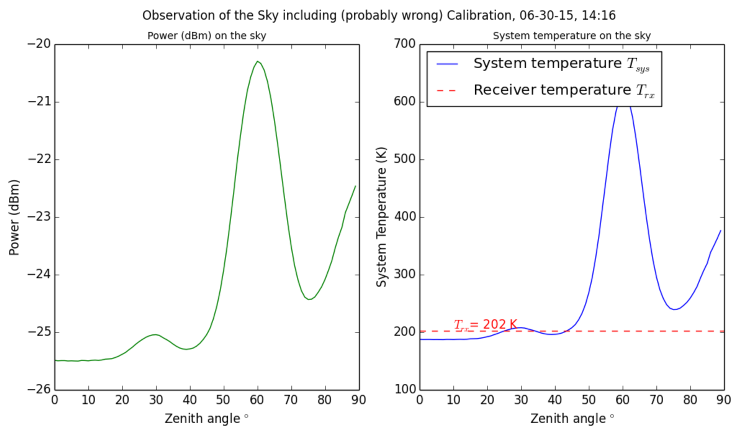


Figure 6.2: Observation made on 06-30-15 at 14:16. The received power show a contradiction to the formula for the system temperature. The system temperature is at the angles of $0° <$ Zenith angle $< 44°$ lower than the receiver noise temperature. This observation measured the powers: $P_{\text{cold}} = -23.7528$ dBm, $P_{\text{hot}} = -21.2085$ dBm and $P_{\text{Zenith}} = -25.4881$ dBm.

loads and therefore a part of the beam is measuring a higher temperature when looking at the cold load.

The simplest explanation is that the beam not entirely filling the load. By measuring the same loads, but now by getting the horn out of the frame and pointing directly at the loads, we are able to be certain about the entire beam filling the loads. Thereafter, the horn was placed back in the system to measure again the hot and cold load. The two measurements turned out to give two different values for the receiver noise temperature, which can be explained by the beam missing the cold load. It could not be caused by measuring the hot load, because the hot load is large and by testing we know for sure that the whole beam is pointed at the hot load. Using the definitions for the Y-factor and effective noise temperature, Zandvliet (2015) is able to state that concerning lab measurements, we effectively measure a cold load temperature of 87.03 K instead of only the temperature of liquid nitrogen, 77.14 K.

6.1 Correction for the cold load temperature

During an observation the telescope gets calibrated by the hot and the cold load. Due to of the importance of this calibration, requiring two load measurements, we have to be sure about the temperature we measure when pointing at our cold load. Zandvliet (2015) already performed measurements of the hot and cold load of the receiver, but to get an idea of the calibration during an observation I repeat the measurement in open air. The following data and plots are obtained by using the script shown in Appendix F.

6.1.1 A hot- and cold load measurement in open air

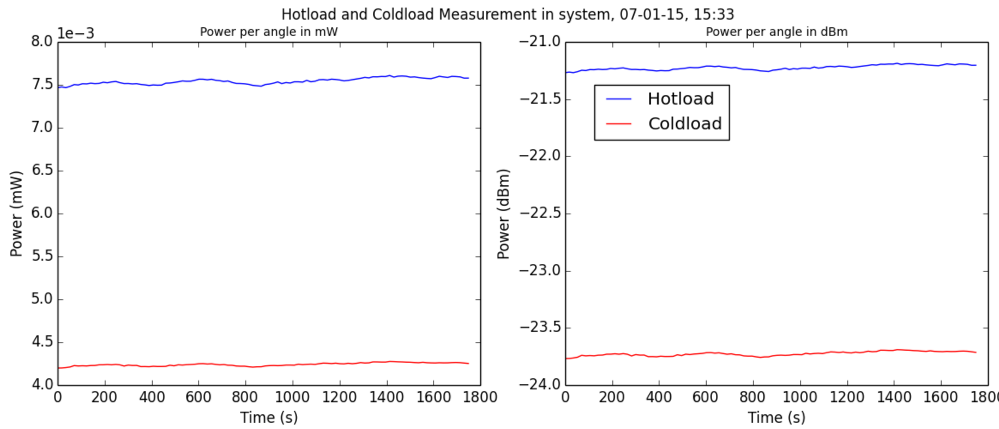


Figure 6.3: Observation made on 07-01-15. Shown in this plot is a measurement of the hot and cold load when the Horn is placed in the frame.

The plots in Figure 6.3 show the powers regarding measuring the hot and the cold load with the horn placed in the frame. We can see a smooth distribution with not a lot of fluctuations. The cold load plotted in red seems to be more stable than the hot load plotted in blue. This could be due to the fact that the hot load temperature will fluctuate with the temperature of the atmosphere, while liquid nitrogen stays approximately the same temperature.

Knowing the power that we measure from the cold load of the system, I measure the power of the cold load by hand to be sure that the entire beam is filled with the liquid nitrogen inside our cold load. Since the measurements could be varying a lot, I will repeat the same measurement three times. These results are shown in Figure 6.4.

For each measurement I calculate the average hot and cold load power together with the average temperature for the hot load. From these values the y-factor for both the measurements of the system and measurements by hand can be determined.

The entire beam is filled with liquid nitrogen by our cold load when doing the measurements by hand. Therefore, we can calculate the effective noise temperature from these values. Knowing these values allows us to determine the effective temperature of the cold load that the beam of the horn 'sees' when placed inside the frame. This gives information about the beam filling factor during our calibration. Using the script shown in Appendix I applying equation (5.1) and (5.3), the values turned out to be as shown in Table 6.1. When looking at these values, it immediately strikes that the calculated temperature is less than the temperature added by the amplifiers (for measurements of the amplifier temperature, see (Zandvliet, 2015)).

Measurement	Average P_{hot}(dBm)	Average P_{cold}(dBm)	Y-factor	T_{rx}(K)	$T_{\text{cold, sys}}$(K)
System	-21.22	-23.73	1.778	—	—
Hand 1	-21.10	-23.72	1.827	209.56	84.86
Hand 2	-21.07	-23.70	1.830	208.43	85.36
Hand 3	-21.07	-23.71	1.837	206.15	86.36

Table 6.1: Data from calibration measurements on 07-01-15. The receiver temperatures are to high, when taking into account that the measured amplifiers were adding a temperature of about 110 K (Zandvliet, 2015) and the received system temperature during observations. Because later on we will use a different way of calibrating our system, the values given in this table will differ from the values in the Logbook. The reason for this will be explained in the coming section. $T_{\text{cold, sys}}$ (K) stands for the new defines temperature of the cold load by using the measurements of, Hand 1, Hand 2, and Hand 3.

The values for the T_{cold} seem to match the expectations about a small part of the beam falling outside the range of the cold load. This means that every time before an observation is made, there has to be a measurement of the hot and the cold load, to confirm the beam missing the cold load and applying a correction for the calibration.

Having an even smaller cold load than expected

As mentioned before, the cold load is to small too fill the entire beam during a calibration sweep. After the measurement done at 07-01-15 we thought T_{cold} could be corrected by getting the horn right in front of the cold load, measuring the load and thereafter placing it back at the frame and measuring the cold load again from that point of view. To be sure, at 07-06-15 I performed the same measurement as done on 07-01-15 again, to check the correction. In the mean time a lot of observations have been done. Therefore, this would be the ultimate check to be sure about the stability of the cold load and the receiver temperature of the telescope.

The measurements done with the telescope included in the frame show that the powers of the hot load and cold load lie at around -20.7 dBm and -23.6 dBm, respectively. This is concluded from the plots shown in Figure 6.5. The measured power value does differ a lot from the measurements done earlier.

This matches the expectations, because the system gain will change during the five days in between the measurements. As I take a look at the measurements done by hand I notice a problem. When measuring the cold load by taking the horn of the frame, the power has to be the same every measurement, because we are looking at the same temperature. It could change a bit because of the changing gain of the telescope itself, but knowing that the measurements of the system are almost identical to the measurements made earlier, the measurements done by hand have to be the same as well, which is not the case. Some difference might be caused by reflections of the horn itself on to the surface of the liquid nitrogen and back into the horn again. These reflections will add power to the received power. Putting the horn at an angle confirms the existence of reflections, because the received power is decreasing by tilting the horn by a little angle.

Comparing Figure 6.4 and 6.6 a cold load power of -23.71 dBm and -23.38 dBm respectively is measured. This difference of 0.33 dBm seems small, but for comparison; having an uncertainty of 0.02 dBm in a single power measurement already induces an uncertainty of 2.27 K in the amplifier noise temperature (see calculations by Zandvliet, 2015).

6.1.2 The 'temporary solution' for the calibration

Due to the fact that the manual measurements and the system measurements differ, I made the conclusion that we can not trust our cold load enough to measure the power response due to the telescope beam being entirely filled by the liquid nitrogen. Luckily, the system response to the cold load stays the same.

The temporary solution for the calibration is measuring again cold load filled with liquid nitrogen and use this measured power as absolute power value signifying a temperature of 77.14 K. At SRON, Sweijen and I looked for a larger cold load for which we could be certain about the entire beam being filled during a measurement. The data taken from the larger cold load are shown in Figure 6.7.

For all observations made earlier, I take into account that a cold load filled with liquid nitrogen being 77.14 K gives a received power of -23.75546 dBm. According to this knowledge and the received cold load power, the temperature of our own cold load can be determined. Thereafter, this temperature and the related power together with the temperature and received power from the hot load can be used to determine the receiver noise temperature and gain during an observation.

In the discussion of this thesis, see Section 9, I will try to find a correlation between the change of the measured cold load temperature, the temperature of the atmosphere and the method of measuring the calibration loads; manual, in the system or during an observation.

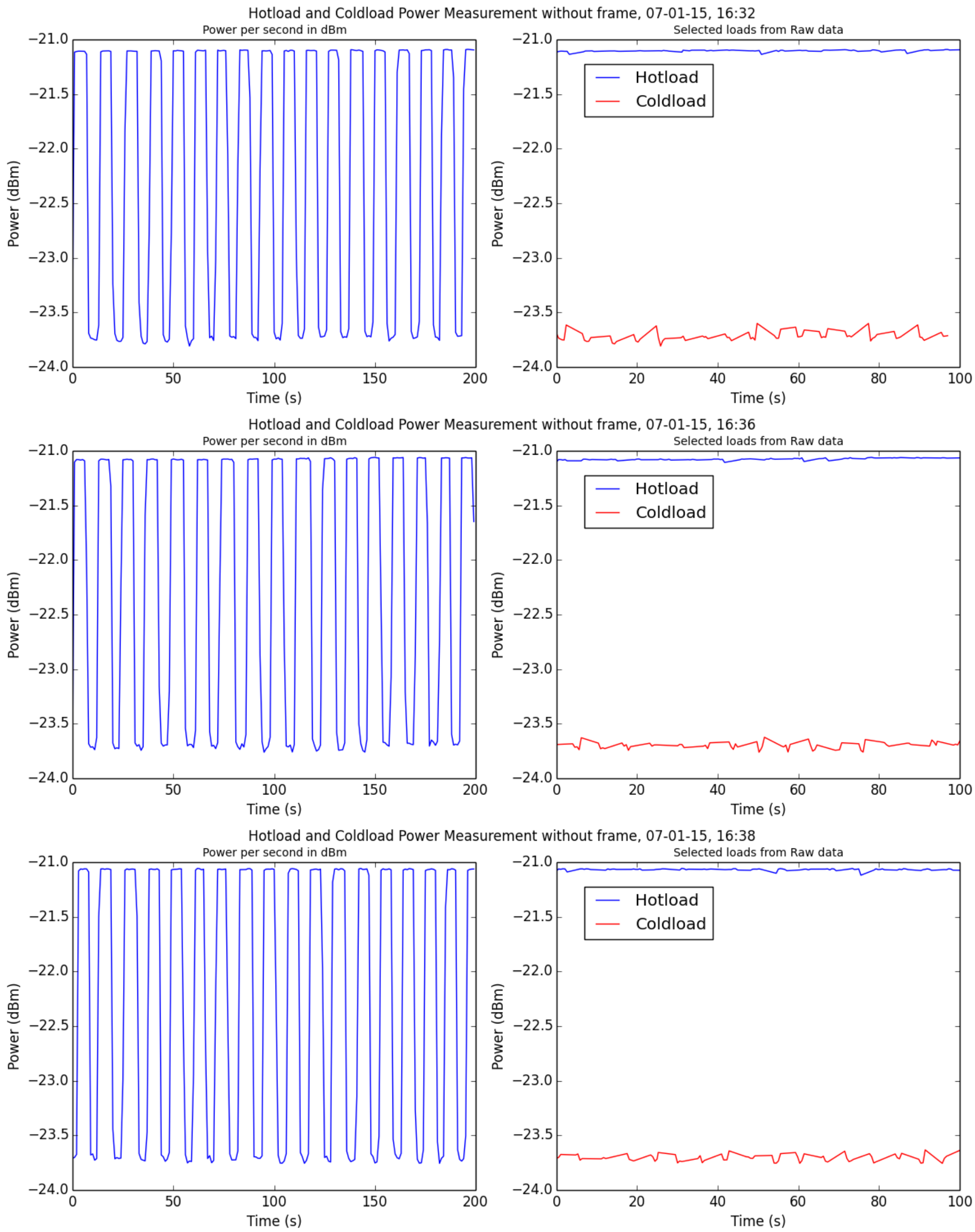


Figure 6.4: Observation made on 07-01-15. A power measurement done by de-constructing the horn from the frame shows the powers measured for the hot load in blue and for the cold load in red. On the left you see the raw data from the measurements. On the right the hot load and cold load are filtered as every measurement above and below a value of -21.15 dBm and -23.6 dBm respectively.

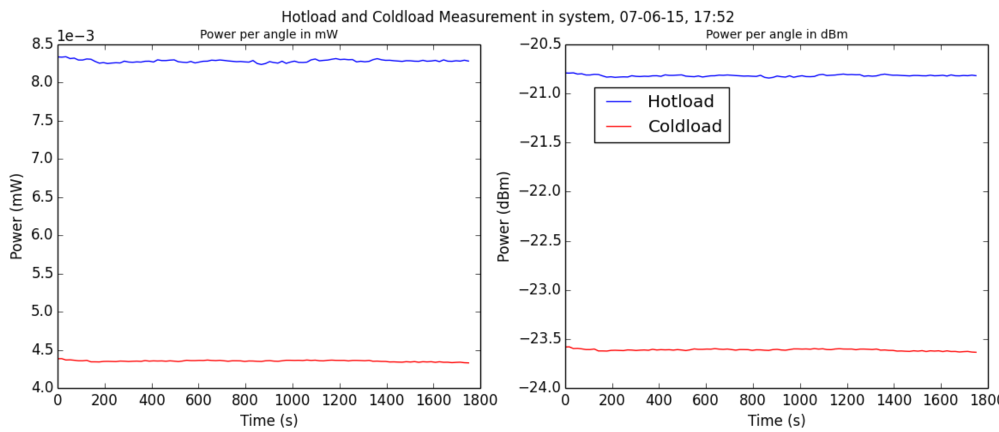


Figure 6.5: Observation made on 07-06-15. Shown in this plot is a measurement of the hot and cold load when the Horn is placed in the frame.

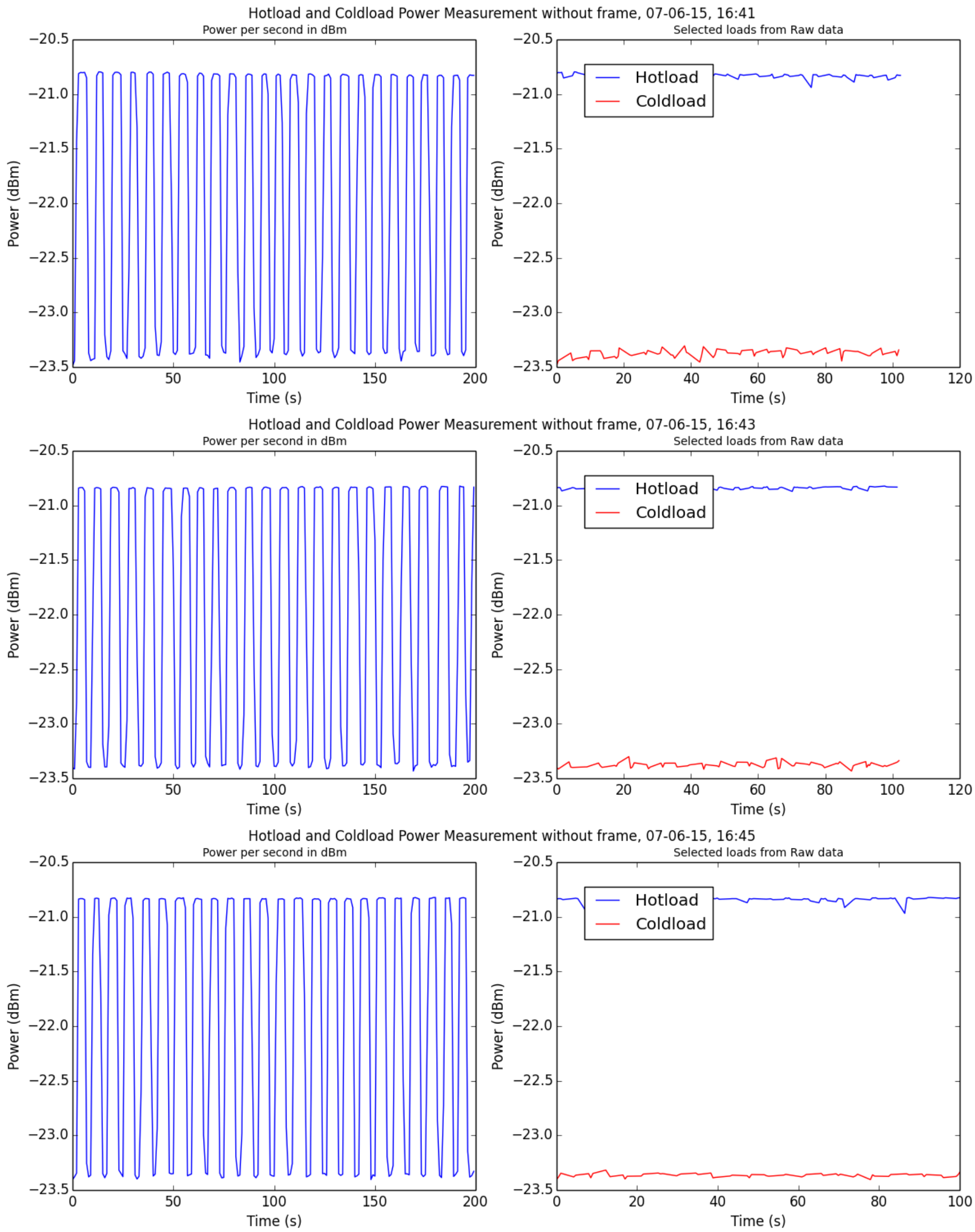


Figure 6.6: Observation made on 07-06-15. A power measurement done by de-constructing the horn from the frame shows the powers measured for the hot load in blue and for the cold load in red. On the left you see the raw data from the measurements. On the right the hot load and cold load are filtered as every measurement above and below a value of -21.0 dBm and -23.3 dBm respectively.

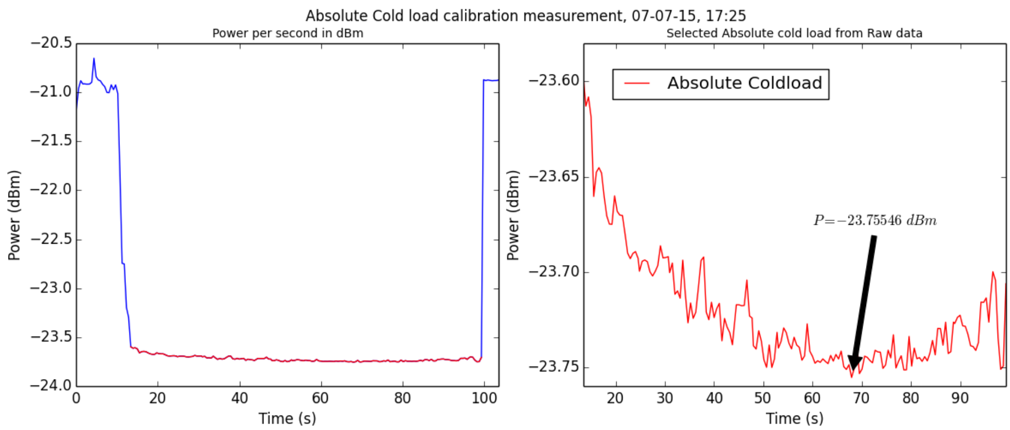


Figure 6.7: Observation made on 07-07-15. Shown in this plot is a measurement of the big cold load, where Sweijen and I could be for sure measuring the liquid nitrogen when taking into account the entire beam.

7 Observations

The main goal of the thesis was to measure the temperature of the CMB. Due to a few problems during the designing, building and testing of the telescope, we were not able to measure T_{cmb} within an accuracy of 10 percent. However, the observations allowed the determination of the zenith opacity τ_0. This chapter is divided into two main observations. From Section 4.2 becomes clear that in order to measure values for τ_0, it is wise to measure the sky on every angle, where measuring T_{cmb} involves measuring every 13° in order to correct for the beam size. To illustrate the data coming from the telescope, I first will describe the first observation of the incoming power coming from the entire system of our telescope.

7.1 Additional observations

Due to the bad calibration and observing one measurement on every angle causing a large uncertainty in the measurement of the system temperature ($\sim$ 3 K), I am not able to state statements requiring temperatures regarding the observations that have been done before 07-09-15. But to give an idea about the incoming power signal into our telescope, I use the observation without any form of calibration. By using this observation I am be able to describe the influence of clouds on our observations.

7.1.1 First on sky test observation

During the day, Monday the 6^{th} of June the telescope saw first light. On the roof terrace of Kapteynborg[1], the radio telescope was set up. It was an unofficial first light, since the 'hot and cold load' calibration was not ready yet. Therefore, the out-coming power could not be converted to a system temperature. As the system temperatures are needed to determine the temperature of the CMB and the value for the opacity, according to equation (3.21), the determination of these quantities could not be completed yet. However, measurements of the Sun could be made to determine the main beam size of the telescope. During the observation, five measurements of the full sky were done, of which the details are in Table 7.1.

The out-coming data of the telescope is a '.txt' file presenting two columns, one containing the angles and one the measured power in dBm. Using the conversion of dBm to mW from equation (5.6), plots are made for each of the five observations. Due to the large steps in angles of the first three observations, the first three plots show a rough line. To determine the main beam, using the Sun, we need a smooth distribution. Therefore, the first three observations were useless regarding the main beam determination. However, the fourth and fifth observation show smooth distributions due to the small sampling size

[1]Landleven 12, 9747 AD, Groningen

Time	T_{atm} (K)	Measure step size (°)	t_{obs}	Remarks
13:00	14	6	0:32	
13:02	14	6	0:32	
13:05	14	4	0:40	
13:08	14	1	1:52	No clouds present
13:12	14	1	1:52	Clouds present

Table 7.1: Details of the five first on sky observations on Monday 06-08-15.

of 1°, see Figure 7.1. These plots can be used to determine the size of the main beam, which is done by Sweijen (2015).

Influence of the clouds Although the temperature of the CMB and the value opacity can not be determined, the influence of the clouds on the incoming power can. Without the presence of clouds, the incoming signal should be higher than when the signal is partly restrained by the clouds. Subtracting the data with the cloudless sky from the cloudy sky, would give the difference, and therefore the dependence of the clouds on the incoming power. This subtraction is shown in Figure 7.2

The peak of the signal coming from the Sun is clearly visible. The maximum value for the power of the Sun in Figure 7.1 is 3.53735×10^{-3} mW, while the maximum value for the difference, presented in Figure 7.2, equals 3.65310×10^{-5} mW. This means that clouds are responsible for one percent of the incoming power signal.

7.2 Opacity observations

7.2.1 Observations 07-09-15

On 07-09-15 the sky was not nice for observations. There were a lot of clouds on the sky. It had been raining that night, therefore the temperature was better than the previous days. Due to time pressure, I decided to put the telescope outside. At the beginning of the observation it was raining a bit. I was standing on the balcony of SRON and was looking in the direction where the telescope aims directly between the Kapteyn and the Duisenberg building (see also Appendix K Section 9).

I used my script to determine the value for the opacity, the error in the fit for the opacity, the uncertainty in the receiver temperature and in addition the uncertainty in the measurement of the system temperature for this data. The script is shown in Appendix G. The determined values are shown in Table 7.3.

From the data it can be concluded that we have a total noise of the system temperature of ~ 1.6 K. This is smaller than T_{cmb} but still higher than the accuracy that we wanted to achieve. It could be due to the fact that I have to take into account a

Time	Measure size (°)	N	T_{atm} (K)	T_{hot} (K)	T_{cold} (K)	Gain (dB)	Description sky
12:49	1	128	290.0	289.7	73.0	60.54	Cloud appearing on the angles $0° < z < 20°$. Until an angle of 30° cloud become less opaque. Till 80° the sky is blue and again at $80° < z < 90°$ there are clouds located.
12:53	1	128	289.5	289.1	96.1	61.52	Cloud appearing on the angles $0° < z < 15°$. Until an angle of 30° cloud become less opaque. Till 80° the sky is blue and again at $80° < z < 90°$ there are clouds located.
12:57	1	128	291.1	290.1	99.7	61.61	Cloud appearing on the angles $0° < z < 20°$. In the range $20° < z < 75°$ the sky is cloudless. At an angle of 75° the sky is cloudy.
13:02	1	256	290.8	292.8	97.0	61.40	Cloud appearing on the angles $0° < z < 15°$. In the range $20° < z < 60°$ the sky is cloudless, with every now and then a little cloud passing by. Until an angle of 75° the sky is blue and from that angle until the horizon the sky gets cloudy.

Table 7.2: Data from observations of the sky made in order to determine the zenith opacity on 07-09-15. Every measurement data point can be a sample of measurements, N. Integrating over these measurements will decrease the uncertainty of the measurement by $\sqrt{\text{N}}$. The cold load is measured after the observation because of the fact that the cold load was too small to fill the entire beam of the antenna.

measurement error for τ_0, when calculating the uncertainty in T_{sys}. The values represented in Table 7.3 are determined by first assuming that every measurement has got an uncertainty of 0.005 in τ_0. Then I take into account that the uncertainty of τ_0 also decreases by $\frac{1}{\sqrt{N}}$, I get the values shown in Table 7.4. The values for the uncertainties shown in Table 7.4 seems to be way more argumentative. The value for τ_0 seems high and variable but expected given the cloud cover. After doing more observations, I expected a value around 0.01, but today the clouds are responsible for the increased value. However, these results show that with poor observation conditions a value of $\tau_0 = 0.023 - 0.032$ is obtained. This is below the worst case value of 0.05 assumed in the simulations.

To be certain about the measurement accuracy, an other observation is made in order to compare the received data.

Time	$\sigma_{T_{\rm rx}}$ (K)	$\sigma_{T_{\rm sys}}$ (K)	τ_0	σ_{τ_0}	Remarks
12:49	0.33	1.55	0.0231	0.0002	
12:53	0.29	1.73	0.0375	0.0002	
12:57	0.29	1.73	0.0368	0.0002	
13:02	0.21	1.63	0.0323	0.0002	Done with 256 measurements instead of 128.

Table 7.3: The calculated τ_0 for the data concerning the observations of 07-09-15. *Note that the values of σ_{τ_0} are not the uncertainties in the value of τ_0, but the uncertainties regarding the fit for the determination of τ_0.*

Time	$\sigma_{T_{\rm rx}}$ (K)	$\sigma_{T_{\rm sys}}$ (K)	τ_0	σ_{τ_0}	Remarks
12:49	0.33	0.34	0.0231	0.00004	128 measurements.
12:53	0.29	0.34	0.0375	0.00004	128 measurements.
12:57	0.29	0.34	0.0368	0.00004	128 measurements.
13:02	0.21	0.24	0.0323	0.00003	256 measurements.

Table 7.4: The calculated τ_0 for taking into account the amount of measurements for the given uncertainty in τ_0. *Note that the values of σ_{τ_0} are not the uncertainties in the value of τ_0, but the uncertainties regarding the fit for the determination of τ_0.*

7.2.2 Observations 07-10-15

(See also Appendix K Section 10) The observations on 07-10-15 where made under the same weather conditions as mentioned in Section 7.2.1. It was the second and last day where I was able to observe the sky while making more measurements at every zenith angle. Again it was not a perfect day for zenith opacity and CMB temperature observations. Although, according to this data I can investigate whether it is possible to observe a zenith opacity which makes sense, when observing without having ideal weather conditions. There were a lot of clouds on the sky.Again there was a little breeze present, and the atmospheric temperature was higher than during the observations of 07-09-15. There was not any rain present. Again, together with Sweijen, I stood on the balcony of SRON and pointed the telescope in the direction where the telescope aims directly between the Kapteyn and the Duisenberg building. I used the same direction as during the observations of 07-09-15 order to be able to investigate whether I will receive a difference in the system temperature. This should be the case according to the changing gain of the telescope and my fixed calibration. According to the data of 07-09-15, doing 256 measurements turned out to be enough to determine precise determine temperatures.

Just as for the data obtained on 07-09-15, by the use of my opacity script I was able to determine the value for the opacity, the error in the fit for the opacity, the uncertainty in the receiver temperature and in addition the uncertainty in the measurement of the system temperature for this data. The values are shown in Table 7.6.

Time	Measure size (°)	N	T_{atm} (K)	T_{hot} (K)	T_{cold} (K)	Gain (dB)	Description sky
13:16	1	256	293.15	295.35	92.0	61.10	
13:20	1	256	293.17	295.02	92.3	61.16	
13:24	1	256	293.0	294.64	93.5	61.22	

Table 7.5: Data from observations of the sky made in order to determine the zenith opacity on 07-10-15. Every measurement data point can be a sample of measurements, N. Integrating over these measurements will decrease the uncertainty of the measurement by $\sqrt{\text{N}}$. The cold load is measured after the observation because of the fact that the cold load was too small to fill the entire beam of the antenna.

Time	$\sigma_{T_{\text{rx}}}$ (K)	$\sigma_{T_{\text{sys}}}$ (K)	τ_0	σ_{τ_0}	Remarks
13:16	0.22	0.25	0.0286	0.00003	256 measurements.
13:20	0.22	0.25	0.0295	0.00003	256 measurements.
13:24	0.22	0.24	0.0300	0.00003	256 measurements.

Table 7.6: The calculated τ_0 for the data concerning the observations of 07-10-15

From these observations it could also be concluded that we have a very stable system. The uncertainty in T_{sys} is small. Making 256 measurements per observation angle even induce the $\sigma_{T_{\text{sys}}}$ being less than 10 percent of T_{cmb}.

7.3 CMB observations

Now we know that we are able to get a value for the opacity from the observations, I can check whether we would be able to measure the temperature of the CMB. During the same days as the observations described in Section 7.2.1 and 7.2.2, sweeps were made having a measurement step of 13°. Therefore I am able to use these observation in order to measure T_{cmb}.

7.3.1 Observations 07-09-15

Time	Measure size (°)	N	T_{atm} (K)	T_{hot} (K)	T_{cold} (K)	Gain (dB)
13:06	13	512	290.9	294.9	64.9	64.93
13:07	13	512	290.9	294.9	68.6	60.23
13:09	13	512	291.0	294.5	71.4	60.49
13:10	13	256	290.7	293.0	85.5	60.90
13:12	13	256	289.9	291.2	90.7	61.23
13:13	13	256	290.1	292.0	92.9	61.21
13:15	13	1024	290.7	293.8	84.5	60.93
13:17	13	1024	290.3	292.0	84.9	60.93

Table 7.7: Data from observations of the sky made in order to determine T_{cmb} with the observation data of 07-09-15. Every measurement data point can be a sample of measurements, N. Integrating over these measurements will decrease the uncertainty of the measurement by $\sqrt{\mathrm{N}}$. The cold load is measured after the observation because of the fact that the cold load was too small to fill the entire beam of the antenna.

By the use of my CMB script I was able to determine the value for the opacity, the error in the fit for the opacity, the value for T_{cmb}, the error in the fit for t_{cmb}, the uncertainty in the receiver temperature and in addition the uncertainty in the measurement of the system temperature for this data. The script is shown in Appendix H.

These observations show that there can be a huge difference in the value for T_{cmb} during a day. The best out coming temperature are those of the observations made on 13:12 and 13:13, shown in figure 7.5. Let's look how they are differ from an observation causing a real bad estimate for T_{cmb}. Bad estimates are for example the temperatures measured during the observation on 13:06 and on 13:07 giving T_{cmb}=-36.31 K and T_{cmb}=-31.06 K respectively. The observations are shown in Figure 7.6.

Time	$\sigma_{T_{rx}}$ (K)	$\sigma_{T_{sys}}$ (K)	τ_0	σ_{τ_0}	T_{cmb} (K)	$\sigma_{T_{cmb}}$ (K)	Remarks
13:06	0.19	0.18	0.0345	0.00003	-36.3178	0.0003	512 measurements.
13:07	0.19	0.18	0.0331	0.00003	-31.0554	0.0003	512 measurements.
13:09	0.18	0.16	0.0350	0.00003	-17.4532	0.0003	512 measurements.
13:10	0.25	0.23	0.0338	0.00003	-5.0161	0.0003	256 measurements.
13:12	0.23	0.21	0.0318	0.00003	4.5232	0.0003	256 measurements.
13:13	0.24	0.22	0.0297	0.00003	2.0892	0.0003	256 measurements.
13:15	0.12	0.11	0.0316	0.00003	-7.3708	0.0003	1024 measurements.
13:17	0.24	0.23	0.0312	0.00003	-5.8648	0.0003	1024 measurements.

Table 7.8: The calculated T_{cmb} and τ_0 for the data concerning the observations of 07-10-15

7.3.2 Observations 07-10-15

More measurements are made which can be used to determine the temperature of the CMB. All observations did make use of different amounts of measurements. Therefore, I am able to state conclusions about the uncertainty becoming more accurate when observing more power measurements at one angle.

Time	Measure size (°)	N	T_{atm} (K)	T_{hot} (K)	T_{cold} (K)	Gain (dB)
13:28	13	256	293.82	295.10	93.3	61.19
13:29	13	256	293.79	295.17	92.7	61.20
13:30	13	256	293.28	294.93	93.3	61.20

Table 7.9: Data from observations of the sky made in order to determine T_{cmb} with the observation data of 07-10-15. Every measurement data point can be a sample of measurements, N. Integrating over these measurements will decrease the uncertainty of the measurement by $\sqrt{\text{N}}$. The cold load is measured after the observation because of the fact that the cold load was too small to fill the entire beam of the antenna.

Just as for the data obtained on 07-09-15, by the use of my CMB script I was able to determine the value for the opacity, the error in the fit for the opacity, the value for T_{cmb}, the error in the fit for t_{cmb}, the uncertainty in the receiver temperature and in addition the uncertainty in the measurement of the system temperature for this data.

Time	$\sigma_{T_{rx}}$ (K)	$\sigma_{T_{sys}}$ (K)	τ_0	σ_{τ_0}	T_{cmb} (K)	$\sigma_{T_{cmb}}$ (K)	Remarks
13:28	0.22	0.24	0.0325	0.00003	5.4930	0.0003	256 measurements.
13:29	0.22	0.24	0.0328	0.00003	5.2989	0.0003	256 measurements.
13:30	0.22	0.24	0.0323	0.00003	5.5008	0.0003	256 measurements.

Table 7.10: The calculated T_{cmb} and τ_0 for the data concerning the observations of 07-10-15

The values obtained do match with the expected τ_0, but the temperature of the CMB is off by about a factor of 2. Although, the $T_{\rm cmb}$ is off, the zenith opacity turns out to have a well defined value this observation day. Unfortunately, I have not got data observed during a day having a clear sky. It might be that we will be able to determine the temperature of the CMB with a clear sky, because we will suffer less from a variable atmospheric opacity.

7.4 Measuring an excess antenna temperature

The results in Section 7.3.1 and 7.3.2 show values for the temperature of the CMB which are very precise, but not accurate. The temperatures vary between ~ 5 K until ~ -37 K. This big difference could be explained by the bad calibration of the data, a fluctuation in the gain or a fluctuation in the atmosphere. To be sure that the CMB is present in the data, we can use the same method as used by Arno Penzias and Robert Wilson. As clarification, they measured a noise temperature from which they knew it was not coming from the ground, atmosphere, pigeons or their receiver.

Figure 7.8 shows an impression about the contribution of the components adding temperature to $T_{\rm sys}$. From the observations we get the system temperature per angle on the sky, which is described by $T_{\rm sys} = T_{\rm cmb}e^{-\tau_0 \sec z} + T_{\rm atm}(1 - e^{-\tau_0 \sec z}) + T_{\rm rx}$. Repeating the discovery requires the following subtracting the contributions of, $T_{\rm atm}$, $T_{\rm rx}$ and the atmosphere itself. From the data, which was mainly obtained to find out the value for τ_0 (see Section 7.2.1 and 7.2.2), I subtract the receiver temperature and the atmospheric contribution. The results obtained show a noise, as can be seen in Figure 7.9 and 7.10.

Looking at the plots, we see two main differences.

1. The dataset of 07-09-15 is smoother than the dataset of 07-10-15. I think this is due to the fluctuations of the atmosphere itself, because the datasets do look the same during the same day. The difference between the plots can be explained by the presence of clouds. Clouds will add to the value for the zenith opacity, and due to $e^{-\tau_{\rm atm}(=\tau_0 \sec z)}$ the exponent will become less. Therefore the temperature will decrease.

2. The peak at the angle of $\sim 85°$. It is an unknown source of ~ 20 K. The source stronger looking at Figure 7.10 than shown in Figure 7.9. This is due to the fact that the source in Figure 7.10 was detected by the main beam and the smaller bump in 7.9 is measured through falling in the range of the side-lobes of the telescope.

The conclusion is made that with our telescope we indeed measure an excess antenna temperature, which is not coming from our system or the atmosphere. The value of ~ 7 K and ~ 5 K differs from the actual value for $T_{\rm cmb}$. This difference is due to a bad calibration, or because our telescope can not measure the CMB that accurate. I think the calibration of our telescope definitely is a main factor of the temperature being off from 2.73 K. To be sure, we have to use a larger cold load in order to be able to calibrate the system properly.

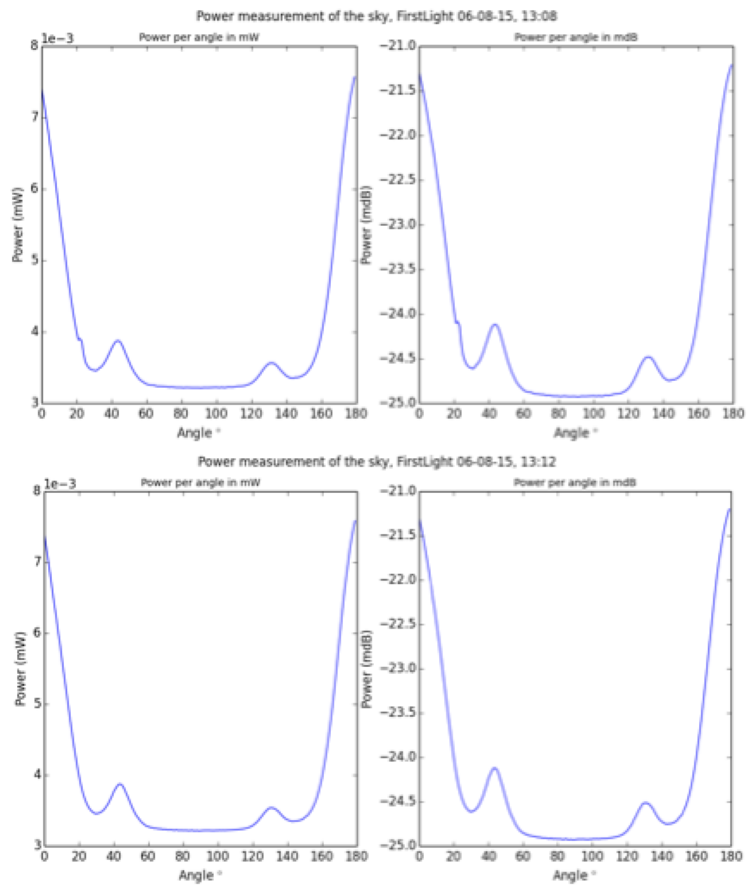


Figure 7.1: The upper plots represent the data taken at 16-08-15 13:08. The peaks from left to right represent the Kapteyn building, John McKean (very small peak), the construction of the telescope itself, the Sun and again the Kapteyn building. During the sampling the Sun was visible. The lower plots represent the data taken at 06-08-15 13:12. The peaks from left to right represent the Kapteyn building, the construction of the telescope itself, the Sun and again the Kapteyn building. During the sampling the Sun was covered by clouds. The plots on the left shows the power values in mW and the plots on the right in dBm.

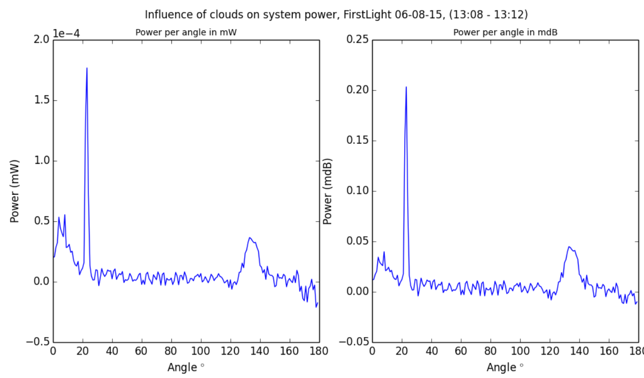


Figure 7.2: The plot above shows the influence of the clouds. The measurement data from the observation with clouds is subtracted from the data without.

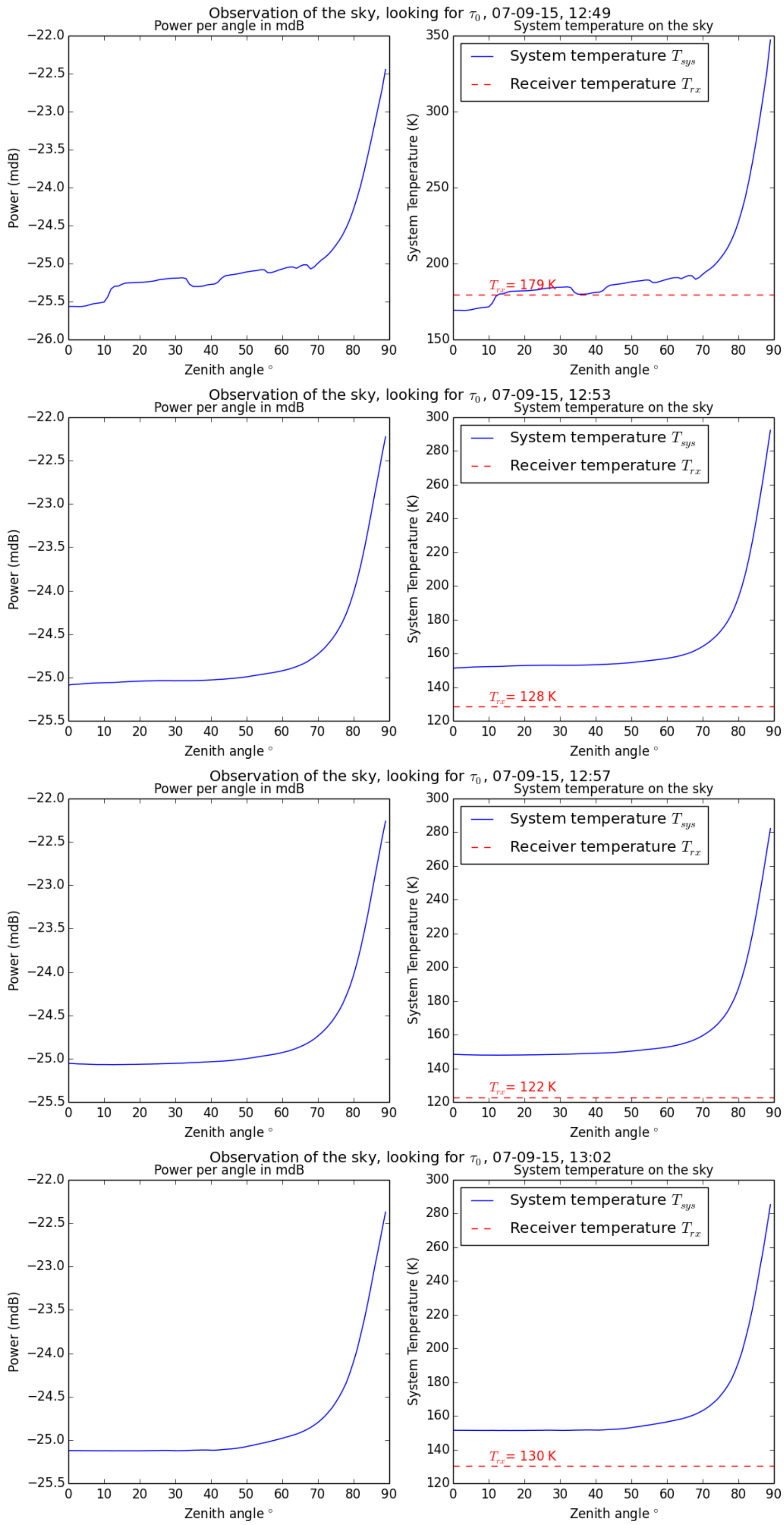


Figure 7.3: Observation made on 07-09-15. These observations were made in order to be able to obtain a value for the opacity. During the observations, it was really cloudy. This could explain the differences in the plots and later on the differences in the value of τ_0

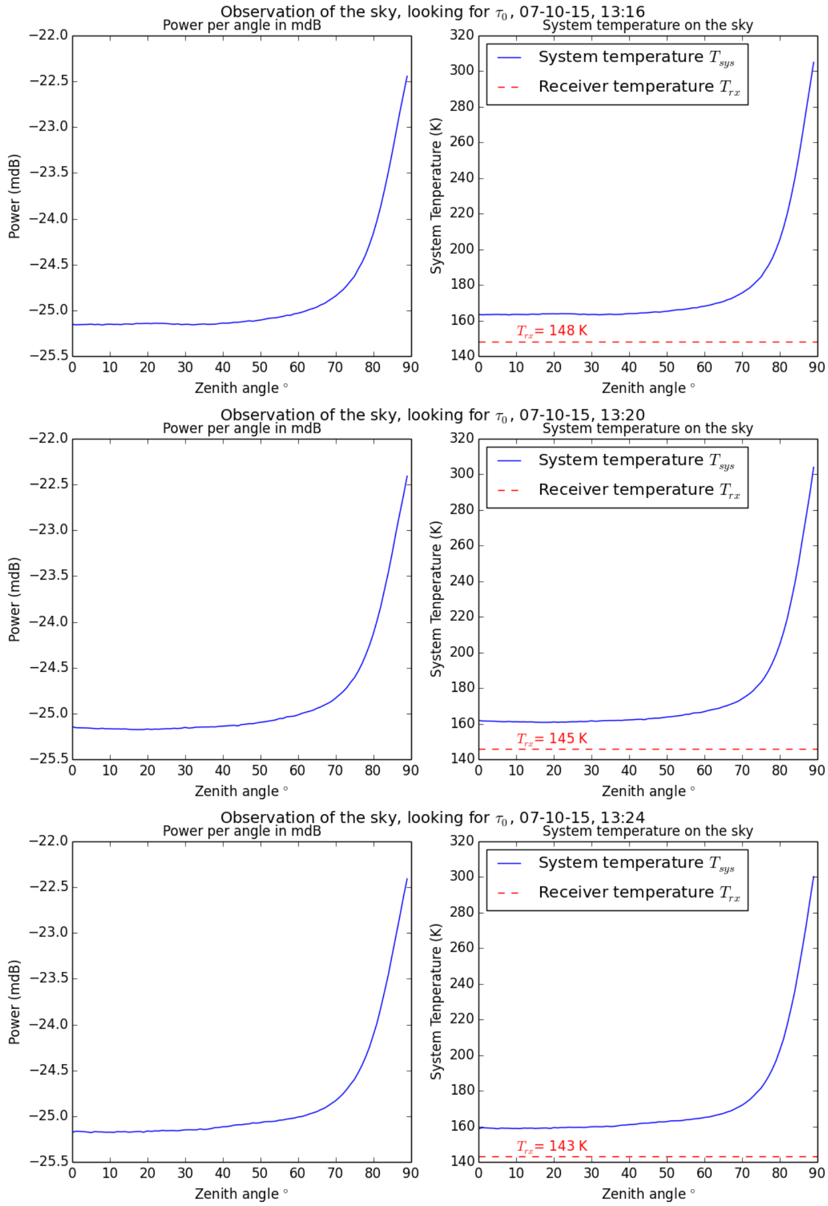


Figure 7.4: Observation made on 07-10-15. These observations were made in order to be able to obtain a value for the opacity. During the observations, the weather conditions were changing very quickly. This could explain the wobbling of $T_{\rm sys}$ for the range $0° < z < 50°$. Having a clear sky, this range should show a straight line.

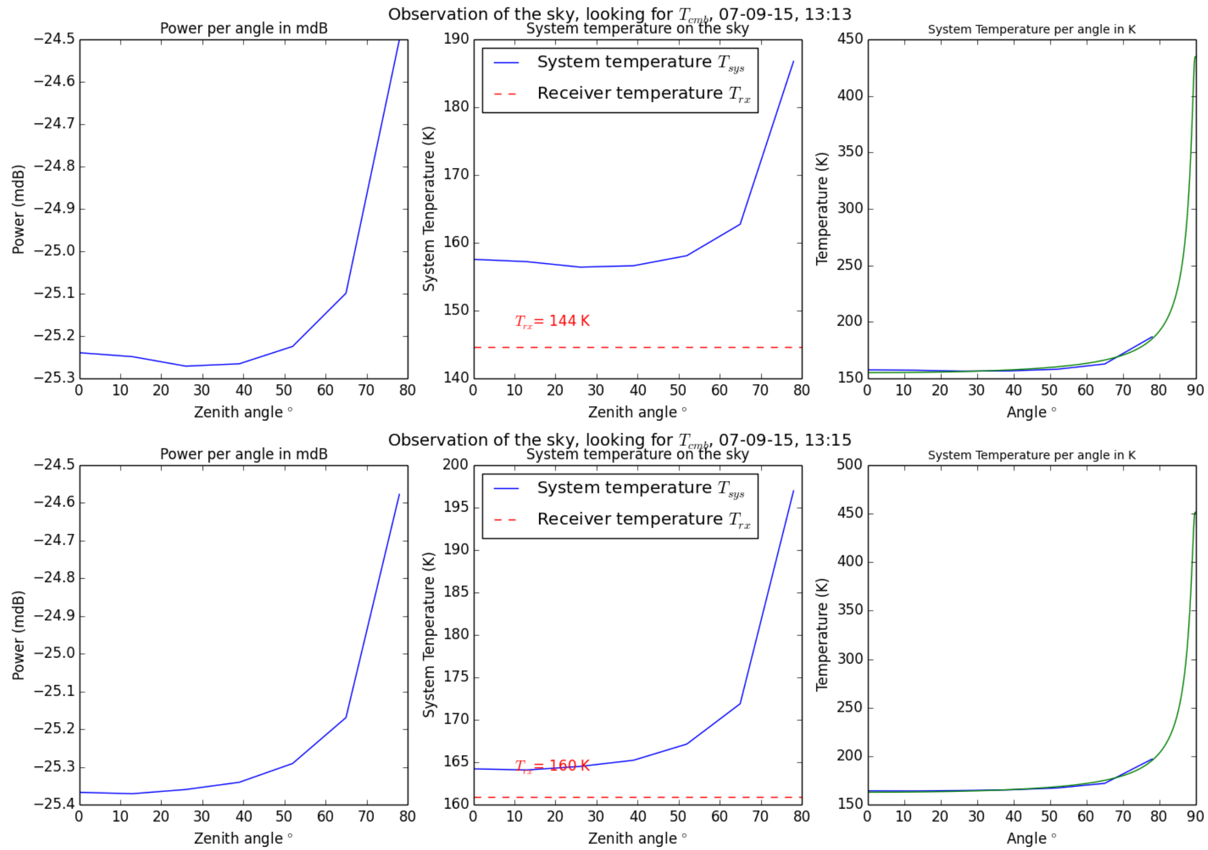


Figure 7.5: Observation made on 07-09-15. These observations were made in order to be able to obtain a value for the T_{cmb}. During the observations, it was cloudy which can cause the bad estimation for τ_0 and therefore for T_{cmb}

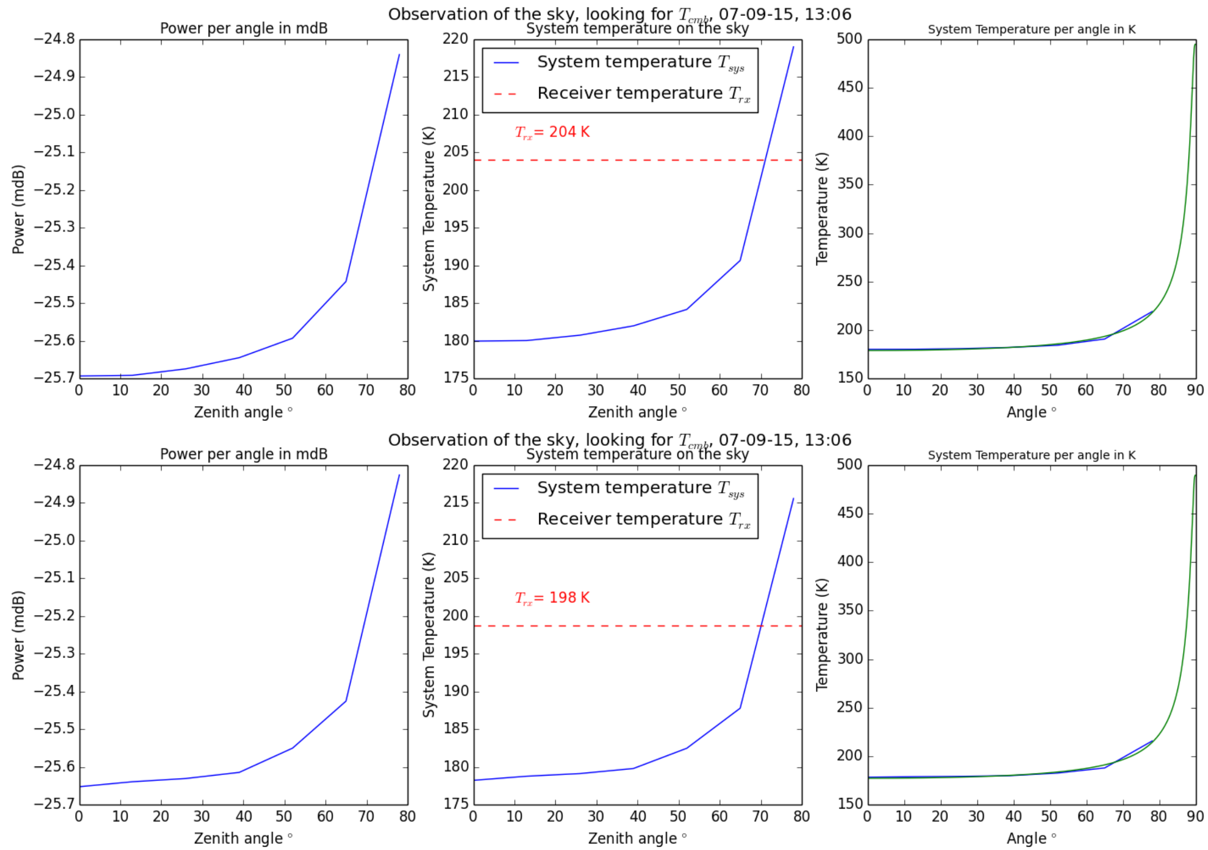


Figure 7.6: Observation made on 07-09-15. These observations were made in order to be able to obtain a value for the $T_{\rm cmb}$. During the observations, it was cloudy which can cause the bad estimation for τ_0 and therefore for $T_{\rm cmb}$

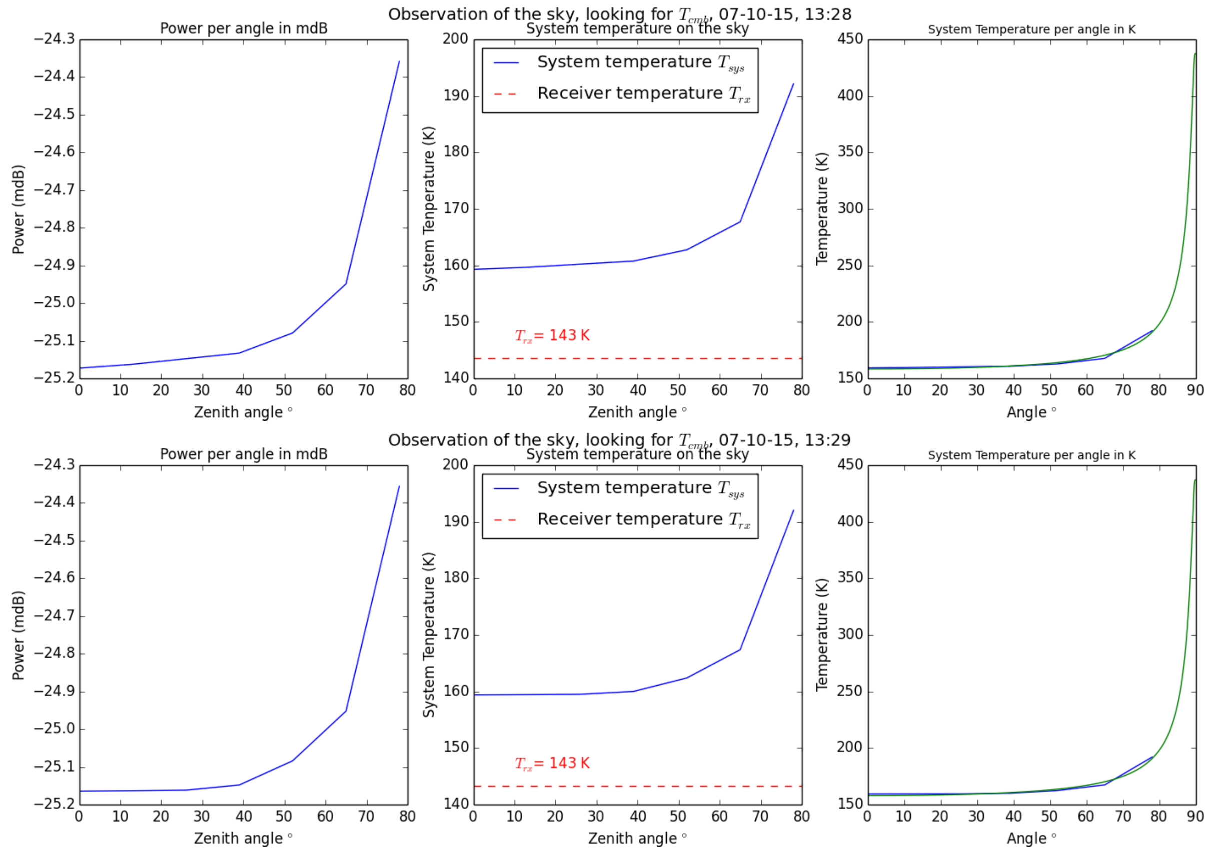


Figure 7.7: Observation made on 07-10-15. These observations were made in order to be able to obtain a value for the $T_{\rm cmb}$. During the observations, it was cloudy which can cause the bad estimation for τ_0 and therefore for $T_{\rm cmb}$

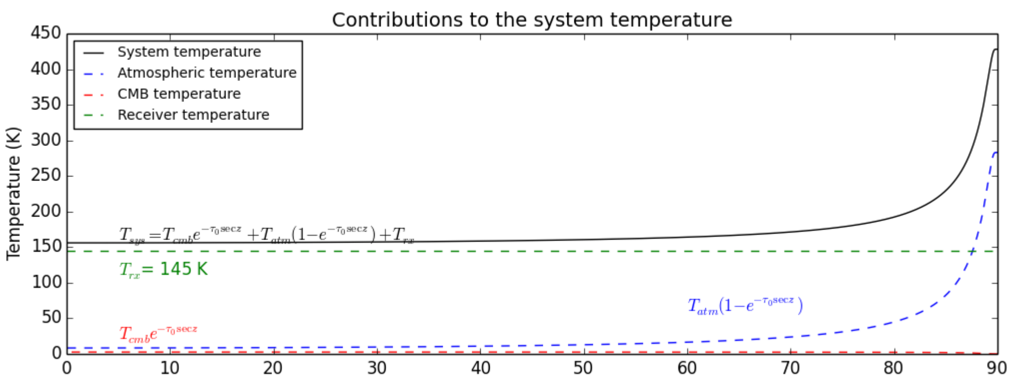
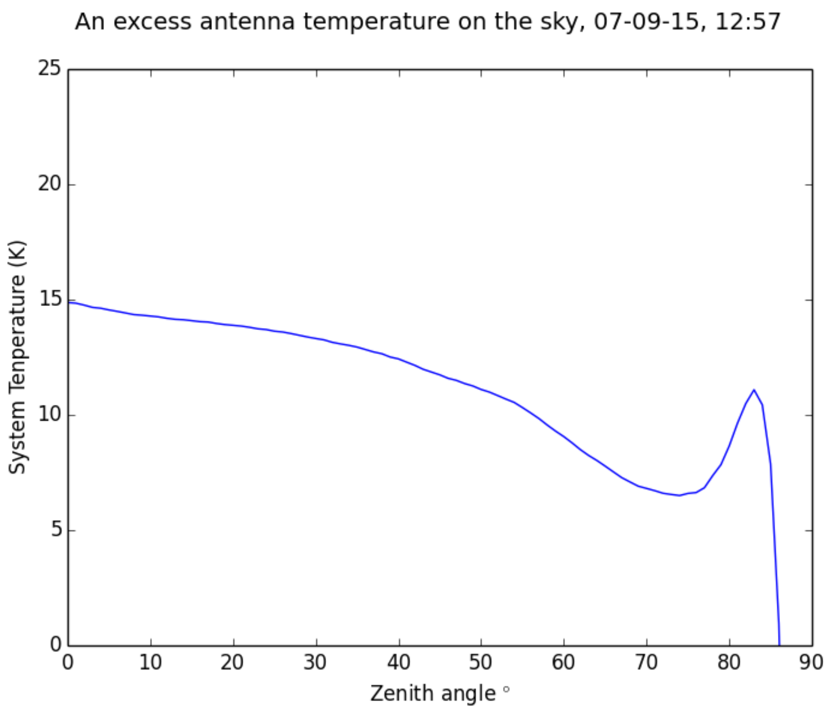


Figure 7.8: A simulation made to give an impression how the different components will contribute to the system temperature. The assumptions made are $T_{\rm atm} = 283$ K, $T_{\rm rx} = 145$ K and $\tau_0 = 0.03$.



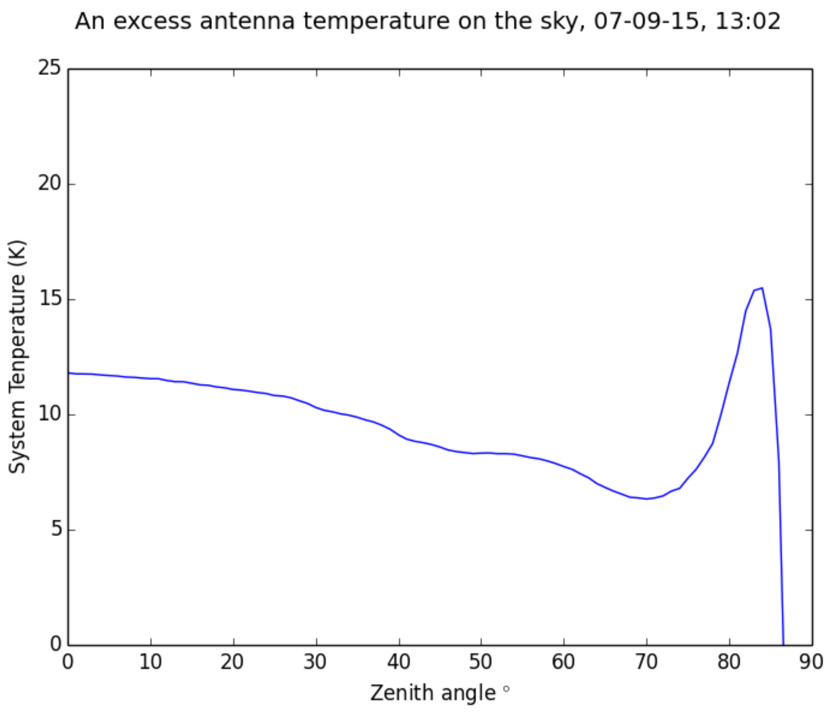
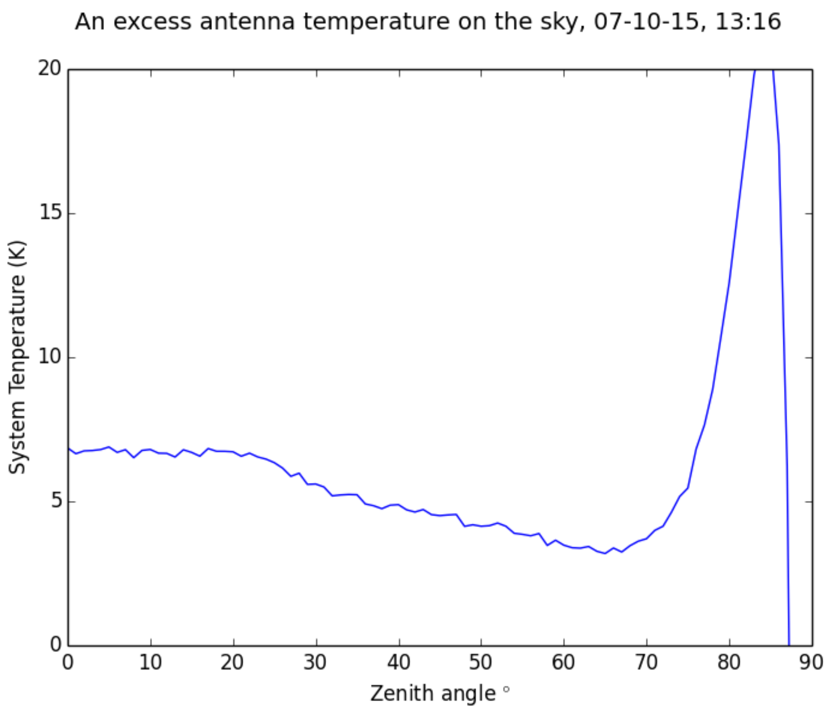


Figure 7.9: Observation made on 07-09-15. The contribution of the atmosphere, atmospheric temperature and from the receiver is subtracted resulting in an excess antenna temperature.



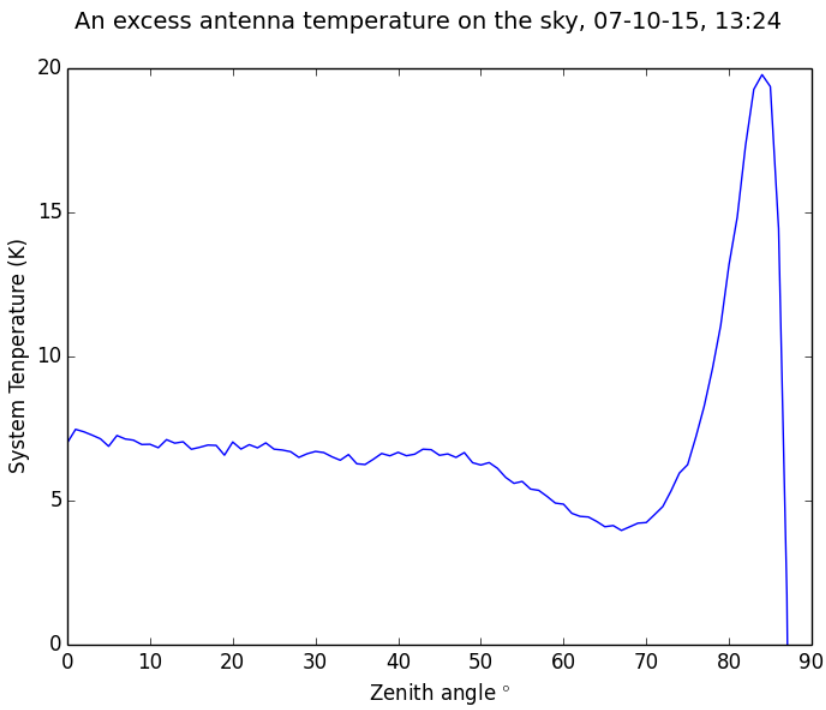


Figure 7.10: Observation made on 07-10-15. These datasets show the results of an excess antenna temperature as seen in Figure 7.9.

8 | Conclusion

8.1 Calibration of the telescope

Regarding the calibration of the telescope, a couple of things were taken into account too late. The conclusion I can state from the project is the following. Due to the fact that our calibration is not working properly, we are not able to convert the incoming powers to temperatures correctly. As we know, our cold load is too small in order to be able to catch the entire beam. This causes a part of the beam seeing the cold load and the part missing the beam a relatively high temperature. Therefore, we simply can not calculate the gain of the telescope, because we do not know which cold load temperature we are actually looking at. As we know, $P = G\Delta\nu kT$, and the fact that the gain of the telescope can change, we can not simply fix a specific power to a temperature. Eventually we did measure an power of liquid nitrogen using a larger cold load in order to be able to correct for our cold load. This is not a good solution, because by applying this fixed power, we are not able take into account the changing gain of the telescope. We used this solution due to time pressure, but ideally we would have used a larger cold load.

To conclude, as we know that applying our absolute cold load temperature does not work, we know that the gain of the telescope is fluctutation. To be able to measure the sky including a proper calibration, we need to arrange a larger cold load.

In Section 9 there will be a full explanation of the problems we had to take in to account during the projects. An overview in the form of a time-line will be given to give an impression about when we found what went wrong.

8.2 Amount of measurements per angle

Appendix K is a overview of the data of all the observations I have done. The reason why I can not use them in order to determine T_{cmb} and τ_0 is that until 07-09-15, we did not know that we had to observe more than one measurement of the incoming power per angle in order to reduce the measurement uncertainty. Due to this realization, we were able to observe for two days applying more measurements per angle. Unfortunately, the whether did not allow us to observe with a clear sky.

8.3 Measurements of the opacity

At the beginning of the project, there was one big question. What is a good estimate for the value for the zenith opacity, τ_0. By studying the literature concerning the Earth's atmosphere and taking a look into data obtained by the Green Bank telescope concerning opacity forecasts, the value for τ_0 is estimated to be 0.05. This value applies to the weather conditions not being ideal. After the observations done at 07-09-15 and 07-10-15 τ_0 could be obtained from the data. The zenith opacity in Groningen by bad weather conditions turns out to have a value varying between 0.0297 and 0.0350 for the observations of 07-09-15 and between 0.0323 and 0.0328 for 07-10-15. It would be interesting to observe again at a day having a clear sky. I expect the value for the opacity to be around 0.01 for these 'ideal' observing conditions.

8.4 Measurements of the CMB

Due to our bad system calibration, caused by a too small cold load, we were not able to observe with a well calibrated system. For the value of the opacity this turned out not to be a big problem. However, according to the observations done to fit a temperature for the CMB, the observations turn out to be not good enough to achieve a T_{cmb} with an accuracy of 10 percent. Each time fitting for T_{cmb} gives an other value. After correction, I was able to measure an excess temperature of the of about 5 K in our system due to the CMB and systematics in the receiver temperature calibration.

Although not every measurement gave the temperature that we had hoped for, we know for sure that we measure an excess antenna temperature. We know for sure that the CMB exists! Further calibration tests will be needed to determine a precise value for the CMB. Further improvements for the coming observations will be discussed in Section 9.

9 Discussion

9.1 What went wrong

In this section, I will give a clear overview of what we found out in which stage of the observing part of our project. This is done by using a time-line.

06-08-15 *First observation of the sky.* During this first observation the only components present on the frame of the telescope where the power meter, the motor and the horn itself. Therefore, we were able to make an first power measurement of the sky. From the data Sweijen (2015) was able to determine the size of our beam pattern. It confirmed the power pattern measured in the lab by Lap (2015).

06-24-15 *First calibrated observation.* During this first calibrated observation, Sweijen and I were able to observe from the terrace of the Kapteyn building. We tried to aim in a direction where we were able to reach the horizon without hitting a building. After the observation plotting the data showed a large power peak at $\sim 70^{\circ}$ when observing in the South direction. This turned out to be a Geostationary Satellite. As we know the satellite has got a fixed location, the only possible clear horizon point seen from the Kapteyn terrace turned out to have a radio source. We had to find a new place in order to observe a clear sky without hitting a source or building.

06-30-15 *Testing the telescope.* During this day we almost had a clear sky. Therefore, Sweijen and I did a lot of measurements during this day. In the afternoon we found a spot where we could observe a source- and building-less sky. This was a spot on the 2^{nd} floor of Kapteyn at the terrace of SRON's conference room. Unfortunately, we only noted a few and lost a lot of information regarding the temperatures that day. During the evening I tried to plot the system temperature of the observations and found out that while doing the right calculations our receiver temperature turned out to be higher than the system temperature. This was impossible.

07-01-15 Calibration measurement. We needed to do a calibration measurement inside and outside to see what was going on. The relative high receiver temperature, ~ 200 K, turned out to be caused by assuming we were looking at a cold load of 77.14 K, while waving around the cold load confirmed that we were missing a part of the beam by measuring the cold load. Doing a hot and cold load measurement inside and outside allowed us to determine a beam filling factor of ~ 0.9. The other 0.1 part of the beam was filled by the temperature of the room, sky, ground and atmospheric temperature. Because we could not now for sure which temperature was contributing to the cold load temperature, we had to figure out another way. By measuring the hot and the cold load by measuring in- and outside the frame we detected a temperature and power difference. We stated that by doing the measurement by hand allowed us to fill the entire beam with liquid nitrogen in order to latter calibrate our system using the measured power as reference for the 'real' cold load. I determined the temperatures of our used cold load using the script shown in Appendix I

07-04-15 and [07-05-15] Daily observations. I decided to measure the sky every day from on this day in order to observe how the system temperature of the telescope is changing. Therefore I thought to be able to state a few statements about the gain of our telescope. The daily observations were based on at least two calibration sweeps, one in at the beginning and one at the end of the observation, and three measurements for each determining the opacity and the temperature of the CMB. I was not able to get on the SRON terrace yet, so that is why all daily measurements are done from the Kapteyn terrace and contain a source on the sky.

07-06-15 Daily observation and calibration. After doing the daily observations I decides to do an other calibrational test to check and confirm that our calibration was working. Instead of confirming I measured a difference of ~ 0.2 dBm in measuring the cold load by taking it out of the system. We thought we were catching the entire beam with the cold load. However, even by pointing the horn straight in front of the load, we were not able to catch the entire beam with the cold load. By tilting the horn, the power went down. This confirmed that measuring right above a load will cause reflections and therefore an increased power load. We had to figure something out to calibrate the system correctly. At this time it was already to late to arrange a new frame and bigger cold load.

07-07-15 *Daily observation.* As I knew we had to correct for the calibration for every observation done untill now, I went on with the observations as done every day. During the evening Sweijen and I went to see our supervisor Prof. dr. A. Baryshev in order to discuss the calibration. We came up with the idea to measure an 'absolute' power by using a larger cold load and poynting the horn slightly tilted above the load. This would be our fixed power to a temperature of liquid nitrogen. From now on, for every measurement we had to calibrate the cold load in our frame by using this fixed power.

07-08-15 Data reduction. During the day I was busy with the data reduction of all observations that had been done. While creating plots Sweijen and I again met our supervisor in order to discuss the measured power the day before. This was when we found out that during all observations we made one measurement at one angle. This was why my error calculations turned out to give errors of about ~ 3 K. Knowing this is higher than the temperature of the CMB itself, it could cause problems. We figured out how to integrate over more ($N = 128$, 256, 512 and 1024) measurements per angle in order to reduce the measurement uncertainty of the power meter by $\frac{0.02\text{ dBm}}{\sqrt{\text{N}}}$. We had to make new observations to state anything relevant about the CMB temperature.

07-09-15 and 07-10-15 *Last possible observing days.* Due to time pressure and bad weather conditions, the observations made these days are the only data taking into account a more precise measurement of the system temperature. This is why I only used these observations to conclude any thing relevant according T_{cmb} and τ_0

Due to the deadline of the thesis I am not able to give conclusions about observations having a clear sky without clouds. i will measure the system temperature as soon as possible. After this project, we will get a larger cold load in order to use the telescope properly for the coming lectures of the course 'Radio Astronomy'.

9.2 Calibration

9.2.1 Possible explanations for the 'wrong' cold load measurements

Too small box for the cold load

Due to the observation done on 07-06-2015, it can be stated that we do not measure a temperature of liquid nitrogen if we point the horn right above the cold load. This impossibility can be explained by comparing Figure 6.5 and 6.6. Looking at both signals received for the cold load, the system shows a lower power than the measurement done by hand. We know from experience that the beam is not entirely filled with the cold load when placed in the system. The power received by hand shows a higher value than the one measured by the system. Therefore, we can infer that if we point straight above the cold load, even a larger part of the beam is 'missing' the cold load. The conclusion that can be made: The cold load is too small. This is already one explanation for the wrong calibration.

Aluminium foil is no good solution

During the last observations included in Appendix K, I saw pieces of the aluminium foil floating through the liquid nitrogen. This can cause extra undesirable reflections and therefore had to be removed. Therefore, I can state that making a possible new and larger cold load, also should take into account to use aluminium plates instead of foil.

Where does the temperature change come from?

Since the time the telescope was ready to use, I made observations concerning the calibration of the telescope during different weather conditions, temperatures and cloudy or non cloudy skies. More information about particular observations can be found in Appendix K.

Concerning these calibration measurements, all important parameters are mentioned in Table 9.1.

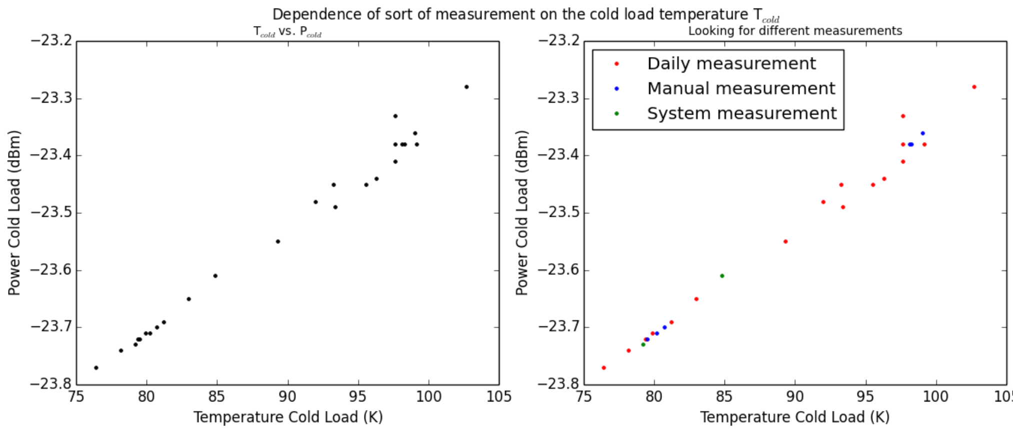


Figure 9.1: The measurements show a linear relation. This is due to the fact that they all have a gain which is more or less equal to each other. On the right, all measurements get distinguished for the method of measuring the hot and the cold load.

I want to investigate, whether I am able to define an expression which calculates the measured temperature of the cold load by inferring which part of the beam we can not catch with our load. If my expectations match, we miss the same percentage of the beam regarding the cold load every time. Because the measurements with hand are made using different observation angles, I will not take these measurements into account. In Figure 9.1 is shown which method is used during the different measurements.

If the higher cold load temperature is due parts of the beam being exposed to the atmospheric temperature, we should see a correlation between a higher T_{atm} and a higher T_{cold}. Plotting the values for these parameters against each other would give a quick view on the dependence of T_{atm} on T_{cold}. The following Figures are made using the script shown in Appendix J.

If we can trust the values and observations, we see from Figure 9.2 that the measurements with a hotter T_{atm} result in a colder T_{cold}. This is in contradiction with the expectations. To confirm that there is no direct relation between T_{atm} and T_{cold}, there should also be no clear solution for

$$T_{\text{cold}} = (1 - x) \cdot T_{\text{abs, cold}} + x \cdot T_{\text{atm}} \tag{9.1}$$

where x is defined as the part of the beam missing the cold load. If the beam is always contributing the same percentage to the beam should occur for the data. Plotting all solutions for equation (9.1) for the data results in Figure 9.3.

Date	T_{atm} (K)	T_{hot} (K)	T_{cold} (K)	P_{hot} (dBm)	P_{cold} (dBm)	T_{rx} (K)	Gain (dB)	Sort[1]
06-30-15	298	300	89.28	-20.97	-23.55	170.49	60.94	1
	298	300	79.90	-21.12	-23.71	190.12	60.41	1
	298	300	76.41	-21.21	-23.77	203.02	60.14	1
	298	300	79.40	-21.13	-23.72	190.78	60.40	1
	298	300	81.23	-21.14	-23.69	192.68	60.40	1
	298	300	78.18	-21.18	-23.74	198.28	60.25	1
07-01-15	305.8	314.14	79.20	-21.22	-23.73	222.50	59.90	3
	305	311	79.51	-21.10	-23.72	200.50	60.24	2
	305	311	80.73	-21.07	-23.70	196.70	60.32	2
	305	311	80.21	-21.06	-23.71	195.62	60.33	2
07-04-15	301.1	301.50	96.29	-21.00	-23.44	175.98	60.99	1
	301.1	303.29	93.39	-21.05	-23.49	184.48	60.78	1
07-05-15	299.1	300.14	97.62	-20.95	-23.41	169.02	61.14	1
	298.1	299.21	95.54	-21.00	-23.45	173.80	61.01	1
07-06-15	294.3	294.79	102.68	-20.78	-23.28	144.53	61.72	1
	294.3	294.79	98.11	-20.83	-23.38	153.17	61.43	2
	294.3	294.79	98.27	-20.84	-23.38	154.98	61.41	2
	294.3	294.79	99.03	-20.84	-23.36	154.79	61.43	2
	296.6	298.97	82.98	-20.88	-23.65	159.37	61.01	1
	297.3	297.39	84.83	-20.82	-23.61	150.65	61.21	3
07-07-15	302.1	300.72	97.62	-20.91	-23.33	164.50	61.31	1
	300.6	299.69	99.16	-20.92	-23.38	164.03	61.26	1
07-09-15	289.7	290.14	97.62	-20.92	-23.38	154.55	61.18	1
07-10-15	293.46	295.49	93.27	-20.77	-23.45	143.48	61.53	1
	295.17	295.63	91.97	-20.79	-23.48	146.01	61.45	1

Table 9.1: During the last week of June '15 and the first two weeks of July '15, a lot of measurements are made to look at the calibration of the telescope. All measurements done are mentioned. For a clear overview see Appendix K.

From this plot we can say that there is no clear solution for equation (9.1). In addition, we can say that the solution seems to be way more constant during one observation day. From this discovery I draw the conclusion that the cold load is not only fluctuating due to

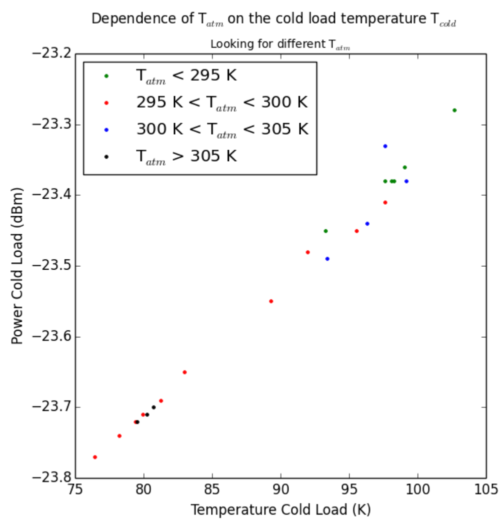


Figure 9.2: The measurements show a linear relation. This is due to the fact that they all have a gain which is more or less equal to each other. On the right, all measurements get distinguished for the method of measuring the hot and the cold load.

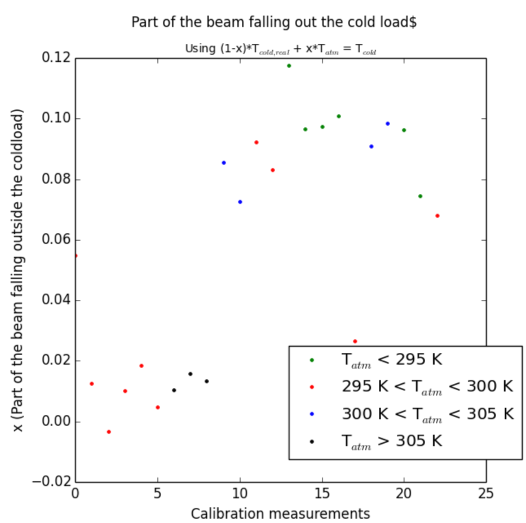


Figure 9.3: The solutions for the equation are spread over the plot.

the atmospheric temperature, but there will also be a fluctuation caused by a fluctuating system gain. It would be useful to investigate this fluctuation of the gain in more detail, but to be able to do that, I need to have a cold load which is for sure stable and big enough to fill the entire beam.

9.3 Recommendations

There are a few recommendations for further and better research.

- Being able to observe the sky preferable requires a clear blue sky without clouds. These days are rare, especially when you live in the Groningen . If a trip to Chile's Atacama desert is not one of the options, I should recommend to do the observations during the winter months when the atmosphere is more dry with respect to the summer months. In addition, a lower atmospheric temperature will also increase the quality of the observing data, due to less contribution of the atmosphere in the system temperature.

- We build a telescope having an observing frequency of 11 GHz. Because of this frequency and our broad beam pattern, we were able to measure the Sun. At the same time, due to the broad beam patter, it sometimes became difficult to not measure the Sun. Observing during the night could be a solution, only during the night we have to take into account the radiation from the Sun being reflected by the moon and the radiation coming from the Milky Way which was standing right above the Groningen sky during the nights in June and July.

- We measure a lot of radiation coming from the buildings. Unfortunately the only spot on the terrace of the Kapteyn which did not had buildings in the field of view, was covered by a lot of radiation (even more than the Sun) due to a Geostationary Satellite. Therefore, the only spot to make a measurement without measuring buildings or radio sources was on the terrace of SRON. It might be useful to get the telescope completely wireless if possible. By making it wireless and maybe even add a battery, we could measure the sky outside the city of Groningen. This will give for sure better results.

- Due to the heaviness and size of the telescope's frame, I was not able to transport the telescope by myself. Because of the sky changing fast, I would recommend to put the frame on wheels in order to be able to get outside and inside as quickly as possible.

- Concerning a better calibration, we need to have a larger cold load in order to be able to catch the entire beam of the horn during the hot and cold load measurements. Only with having a good calibration I would have been able to state something about the changing gain of the telescope. Now, because of our calibration problem, we are not able to distinguish a changing gain from an bad calibration measurement and from a change in the (atmospheric or hot and cold load) temperature.

- Having a larger cold load requires more liquid nitrogen. Our cold load already needed 10 litres to be entirely filled. Through this, we have used at least an amount of 300 litres. This huge amount is mostly due to the fact that we had to throw the liquid nitrogen what was left away because we were not able to store it again. If we are able to store, we are able to reduce the amounts of used nitrogen by a lot.

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A Derivation arithmetic exact formula.

Defining the sample mean and the variance as

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad \sigma_x^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2 \tag{A.1}$$

Using a linear approximation of $f(x)$ near $\hat{x}$ such that $f - \hat{f} \approx \frac{\partial f}{\partial x}(x - \hat{x})$. Having this expression, the true values of x and $f(x)$ lie in the ranges of $x = \hat{x} \pm \delta x$ and $f(x) = \hat{f} \pm \delta f$, where δf can be written as $\delta f = \left|\frac{\partial f}{\partial x}\right| \delta x$. Having more variables the expression becomes

$$f - \bar{f} = \frac{\partial f}{\partial x}(x - \bar{x}) + \frac{\partial f}{\partial y}(y - \bar{y}) \tag{A.2}$$

Using equation (A.2) and the expression for the variance, we find

$$\sigma_f^2 = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x}(x - \bar{x}) + \frac{\partial f}{\partial y}(y - \bar{y})\right)^2 \tag{A.3}$$

The expansion of equation A.3 therefore leads to

$$\sigma_f^2 = \frac{1}{N-1}\left(\left(\frac{\partial f}{\partial x}\right)^2\sum_{i=1}^{N}(x - \bar{x})^2 + \left(\frac{\partial f}{\partial y}\right)^2\sum_{i=1}^{N}(y - \bar{y})^2 + 2\frac{\partial f}{\partial x}\frac{\partial f}{\partial y}\sum_{i=1}^{N}(x - \bar{x})(y - \bar{y})\right) \tag{A.4}$$

Now again using the definition for the variance expressed in equation (A.1), equation (A.4) can be written as

$$\sigma_f^2 = \left(\frac{\partial f}{\partial x}\right)^2\sigma_x^2 + \left(\frac{\partial f}{\partial y}\right)^2\sigma_y^2 + 2\frac{\partial f}{\partial x}\frac{\partial f}{\partial y}\sigma_{xy}^2 \tag{A.5}$$

Neglecting the correlation terms, the general formula for the variance can be written as

$$\sigma_f = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2\sigma_x^2 + \left(\frac{\partial f}{\partial y}\right)^2\sigma_y^2 + \left(\frac{\partial f}{\partial z}\right)^2\sigma_z^2 + \dots} \tag{A.6}$$

(of Maryland, 2006)

Using differentials is a way to propagate uncertainties. In addition, an other way is using a method called "arithmetic calculations of error propagation". This implies the following expressions, that also could also be used for the uncertainty propagation calculations.

$$\begin{aligned} f &= a + b - c & \sigma_f &= \sqrt{\sigma_a^2 + \sigma_b^2 + \sigma_c^2} \\ f &= a \times \frac{b}{c} & \frac{\sigma_f}{f} &= \sqrt{\left(\frac{\sigma_a}{a}\right)^2 + \left(\frac{\sigma_b}{b}\right)^2 + \left(\frac{\sigma_c}{c}\right)^2} \\ f &= a^y & \frac{\sigma_f}{f} &= y\left(\frac{\sigma_a}{a}\right) \end{aligned} \tag{A.7}$$

B Simulation to determine an useful number of measurements regarding opacity.

```
#!/usr/bin/env python

from __future__ import division
from matplotlib import pyplot
from matplotlib.pyplot import figure , show

from scipy.optimize import curve_fit

import random

from matplotlib.pyplot import *

import math
import numpy as np

''' Definitions for the variables '''
tau_0 = 0.05 #(assumed)

elevation = np.arange(0,90,0.01)
z = (90 - elevation)
z = np.radians(z)

k = 1.3807e-23 # J * K^-1

T_cmb = 2.73 #K
T_atm = 283 #K

''' Calculating atmosperic opacity '''
def sec(z):
    return (1/ np.cos(z))

def tau_atm(z, t_0):
    tau =t_0 * sec(z)
    return tau

''' Calulating oberved temperature according to the opacity '''
def T_antenna(tau, T_atm):
    T = T_cmb * np.exp(-tau) + T_atm *(1-np.exp(-tau))
    return T

def func(z, tau_0):
    return ( T_cmb * np.exp(- tau_atm(z, tau_0)) ) + ( T_atm * (1 - np.exp(- tau_atm(z,
        tau_0))) )

''' Generating errors in tau_0 '''
tau_0err1 = np.random.normal(tau_0, 0.001 ,9000)
tau_0err2 = np.random.normal(tau_0, 0.002 ,9000)
tau_0err3 = np.random.normal(tau_0, 0.005 ,9000)
tau_0err4 = np.random.normal(tau_0, 0.01 ,9000)


''' Calculating T_A for the random generated tau_0s '''
```

```
TA1 = T_antenna(tau_atm(z, tau_0err1), T_atm)
TA2 = T_antenna(tau_atm(z, tau_0err2), T_atm)
TA3 = T_antenna(tau_atm(z, tau_0err3), T_atm)
TA4 = T_antenna(tau_atm(z, tau_0err4), T_atm)


''' Plotting'''
fig = figure(figsize=(14,9))
fig.suptitle('Dependence of uncertainties in $\\tau_0$ on $T_A = T_{cmb}e^{-\\tau_0 \\
    sec z} + T_{atm}(1-e^{-\\tau_0 \\sec z})$', fontsize=18)
frame = fig.add_subplot(2,2,1)
frame.set_title('Uncertainty of $\\Delta \\tau_0 = 0.001$', fontsize='14')
frame.plot(np.degrees(z), TA1, color='blue', label='$\\tau_{atm}$')
pyplot.xlabel('Zenith angle $\\degree$')
pyplot.ylabel('Antenna temperature (K)')

frame = fig.add_subplot(2,2,2)
frame.set_title('Uncertainty of $\\Delta \\tau_0 = 0.002$', fontsize='14')
frame.plot(np.degrees(z), TA2, color='blue', label='$\\tau_{atm}$')
pyplot.xlabel('Zenith angle $\\degree$')
pyplot.ylabel('Antenna temperature (K)')

frame = fig.add_subplot(2,2,3)
frame.set_title('Uncertainty of $\\Delta \\tau_0 = 0.005$', fontsize='14')
frame.plot(np.degrees(z), TA3, color='blue', label='$\\tau_{atm}$')
pyplot.xlabel('Zenith angle $\\degree$')
pyplot.ylabel('Antenna temperature (K)')

frame = fig.add_subplot(2,2,4)
frame.set_title('Uncertainty of $\\Delta \\tau_0 = 0.01$', fontsize='14')
frame.plot(np.degrees(z), TA4, color='blue', label='$\\tau_{atm}$')
pyplot.xlabel('Zenith angle $\\degree$')
pyplot.ylabel('Antenna temperature (K)')
fig.subplots_adjust(hspace=.3)
fig.savefig('Opacityequation.png')

sample2 = [2250, 6750]
sample5 = [1500, 3000, 4500, 6000, 7500]
sample10 = [750, 1500, 2250, 3000, 3750, 4500, 5250, 6000, 6750, 7500]
sample90 = np.arange(0,90,1)

elevation = np.arange(0,90,1)
z = (90 - elevation)
z = np.radians(z)

''' Calculating the values for the opacity having an amount of samples and measurements
    '''

avtau = []
avuntau = []

for k in range(1):
    angle =[]
    antenna =[]
    for i in sample90:
        tau_0err1 = np.random.normal(tau_0, 0.005 ,90)
        TA1 = T_antenna(tau_atm(z, tau_0err1), T_atm)
        angle.append(z[i])
        antenna.append(TA1[i])
    avtau.append(curve_fit(func, angle, antenna, maxfev=10000)[0])
    avuntau.append(curve_fit(func, angle, antenna, maxfev=10000)[1])
print '1 measurement of 90 samples of 0.01'
print np.mean(avtau)
```

```
print np.mean(avuntau)

avtau = []
avuntau = []

for k in range(5):
    angle =[]
    antenna =[]
    for i in sample90:
        tau_0err1 = np.random.normal(tau_0, 0.005 ,90)
        TA1 = T_antenna(tau_atm(z, tau_0err1), T_atm)
        angle.append(z[i])
        antenna.append(TA1[i])
    avtau.append(curve_fit(func, angle, antenna, maxfev=10000)[0])
    avuntau.append(curve_fit(func, angle, antenna, maxfev=10000)[1])
print '5 measurements of 90 samples of 0.01'
print np.mean(avtau)
print np.mean(avuntau)

avtau = []
avuntau = []

for k in range(10):
    angle =[]
    antenna =[]
    for i in sample90:
        tau_0err1 = np.random.normal(tau_0, 0.005 ,90)
        TA1 = T_antenna(tau_atm(z, tau_0err1), T_atm)
        angle.append(z[i])
        antenna.append(TA1[i])
    avtau.append(curve_fit(func, angle, antenna, maxfev=10000)[0])
    avuntau.append(curve_fit(func, angle, antenna, maxfev=10000)[1])
print '10 measurements of 90 samples of 0.01'
print np.mean(avtau)
print np.mean(avuntau)

avtau = []
avuntau = []

for k in range(50):
    angle =[]
    antenna =[]
    for i in sample90:
        tau_0err1 = np.random.normal(tau_0, 0.005 ,90)
        TA1 = T_antenna(tau_atm(z, tau_0err1), T_atm)
        angle.append(z[i])
        antenna.append(TA1[i])
    avtau.append(curve_fit(func, angle, antenna, maxfev=10000)[0])
    avuntau.append(curve_fit(func, angle, antenna, maxfev=10000)[1])
print '50 measurements of 90 samples of 0.01'
print np.mean(avtau)
print np.mean(avuntau)

avtau = []
avuntau = []

for k in range(100):
    angle =[]
    antenna =[]
    for i in sample90:
        tau_0err1 = np.random.normal(tau_0, 0.005 ,90)
        TA1 = T_antenna(tau_atm(z, tau_0err1), T_atm)
        angle.append(z[i])
```

```
        antenna.append(TA1[i])
    avtau.append(curve_fit(func, angle, antenna, maxfev=10000)[0])
    avuntau.append(curve_fit(func, angle, antenna, maxfev=10000)[1])
print '100 measurements of 90 samples of 0.01'
print np.mean(avtau)
print np.mean(avuntau)

avtau = []
avuntau = []

for k in range(500):
    angle =[]
    antenna =[]
    for i in sample90:
        tau_0err1 = np.random.normal(tau_0, 0.005 ,90)
        TA1 = T_antenna(tau_atm(z, tau_0err1), T_atm)
        angle.append(z[i])
        antenna.append(TA1[i])
    avtau.append(curve_fit(func, angle, antenna, maxfev=10000)[0])
    avuntau.append(curve_fit(func, angle, antenna, maxfev=10000)[1])
print '500 measurements of 90 samples of 0.01'
print np.mean(avtau)
print np.mean(avuntau)
```

C | Simulation to determine an useful number of measurements regarding CMB.

```
#!/usr/bin/env python

from __future__ import division
from matplotlib import pyplot
from matplotlib.pyplot import figure, show

from scipy.optimize import curve_fit

import random

from matplotlib.pyplot import *

import math
import numpy as np

''' Definitions for the variables '''
tau_0 = 0.05 #(assumed)

elevation = np.arange(0,90,0.01)
z = (90 - elevation)
z = np.radians(z)

k = 1.3807e-23 # J * K^-1

T_cmb = 2.73 #K
T_atm = 283 #K

''' Calculating atmosperic opacity '''
def sec(z):
    return (1/ np.cos(z))

def tau_atm(z, t_0):
    tau =t_0 * sec(z)
    return tau

''' Calulating oberved temperature according to the opacity '''
def T_antenna(z, tau, T_atm):
    T = 2.73 * np.exp(-tau_atm(z, tau)) + T_atm *(1-np.exp(-tau_atm(z, tau)))
    return T

def func(z, T_cmb):
    return ( T_cmb * np.exp(- tau_atm(z, tau_0)) ) + ( T_atm * (1 - np.exp(- tau_atm(z,
        tau_0))) )

elevation = np.arange(0,90,1)
z = (90 - elevation)
z = np.radians(z)

sample2 = [22, 67]
sample5 = [15, 30, 45, 60, 75]
sample10 = [7, 15, 22, 30, 37, 45, 52, 60, 67, 75]
```

```python
def func(z, T_cmb):
    return ( T_cmb * np.exp(- tau_atm(z, tau_0)) ) + ( T_atm * (1 - np.exp(- tau_atm(z,
        tau_0))) )

avcmb= []
avuncmb = []

for k in range(500):
    angle =[]
    antenna =[]
    for i in sample2:
        tau_0err1 = np.random.normal(tau_0, 0.001 ,90)
        TA = T_antenna(z, tau_0err1, T_atm)
        angle.append(z[i])
        antenna.append(TA[i])
    avcmb.append(curve_fit(func, angle, antenna, maxfev=1000)[0])
    avuncmb.append(curve_fit(func, angle, antenna, maxfev=1000)[1])
print '10 measurements of 2 samples'
print np.mean(avcmb)
print np.mean(avuncmb)

avcmb= []
avuncmb = []

for k in range(500):
    angle =[]
    antenna =[]
    for i in sample5:
        tau_0err1 = np.random.normal(tau_0, 0.001 ,90)
        TA = T_antenna(z, tau_0err1, T_atm)
        angle.append(z[i])
        antenna.append(TA[i])
    avcmb.append(curve_fit(func, angle, antenna, maxfev=1000)[0])
    avuncmb.append(curve_fit(func, angle, antenna, maxfev=1000)[1])
print '10 measurements of 5 samples'
print np.mean(avcmb)
print np.mean(avuncmb)

avcmb= []
avuncmb = []

for k in range(500):
    angle =[]
    antenna =[]
    for i in sample10:
        tau_0err1 = np.random.normal(tau_0, 0.001 ,90)
        TA = T_antenna(z, tau_0err1, T_atm)
        angle.append(z[i])
        antenna.append(TA[i])
    avcmb.append(curve_fit(func, angle, antenna, maxfev=1000)[0])
    avuncmb.append(curve_fit(func, angle, antenna, maxfev=1000)[1])
print '10 measurements of 10 samples'
print np.mean(avcmb)
print np.mean(avuncmb)
```

D | Propagation of errors

D.1 Y-factor

Having equation (5.1), the expression for the Y-factor having powers in dBm becomes

$$Y = 10^{\frac{P_{\text{hot}} - P_{\text{cold}}}{10}} \tag{D.1}$$

Using this expression, we can apply propagation of errors through

$$\sigma_Y = \sqrt{\left(\frac{\partial Y}{\partial P_{\text{hot}}}\right)^2 \sigma^2_{P_{\text{hot}}} + \left(\frac{\partial Y}{\partial P_{\text{cold}}}\right)^2 \sigma^2_{P_{\text{cold}}}} \tag{D.2}$$

$$\begin{aligned}
\left(\frac{\partial Y}{\partial P_{\text{hot}}}\right) &= \frac{\partial}{\partial P_{\text{hot}}}\left(10^{\frac{P_{\text{hot}} - P_{\text{cold}}}{10}}\right) &&= \log_{10} \cdot 10^{\frac{P_{\text{hot}} - P_{\text{cold}} - 10}{10}} \\
\left(\frac{\partial Y}{\partial P_{\text{cold}}}\right) &= \frac{\partial}{\partial P_{\text{cold}}}\left(10^{\frac{P_{\text{hot}} - P_{\text{cold}}}{10}}\right) &&= -\log_{10} \cdot 10^{\frac{P_{\text{hot}} - P_{\text{cold}} - 10}{10}}
\end{aligned}$$

D.2 Receiver temperature

Using the expression for the receiver temperature, see equation (5.3), propagation of errors lead to

$$\sigma_{T_{\text{rx}}} = \sqrt{\left(\frac{\partial T_{\text{rx}}}{\partial P_{\text{hot}}}\right)^2 \sigma^2_{P_{\text{hot}}} + \left(\frac{\partial T_{\text{rx}}}{\partial P_{\text{cold}}}\right)^2 \sigma^2_{P_{\text{cold}}} + \left(\frac{\partial T_{\text{rx}}}{\partial Y}\right)^2 \sigma^2_Y} \tag{D.3}$$

$$\begin{aligned}
\left(\frac{\partial T_{\text{rx}}}{\partial P_{\text{hot}}}\right) &= \frac{\partial}{\partial P_{\text{hot}}}\left(\frac{T_{\text{hot}} - T_{\text{cold}}Y}{Y-1}\right) &&= \frac{1}{(Y-1)} \\
\left(\frac{\partial T_{\text{rx}}}{\partial P_{\text{cold}}}\right) &= \frac{\partial}{\partial P_{\text{cold}}}\left(\frac{T_{\text{hot}} - T_{\text{cold}}Y}{Y-1}\right) &&= \frac{-Y}{(Y-1)} \\
\left(\frac{\partial T_{\text{rx}}}{\partial Y}\right) &= \frac{\partial}{\partial Y}\left(\frac{T_{\text{hot}} - T_{\text{cold}}Y}{Y-1}\right) &&= \frac{(T_{\text{cold}} - T_{\text{hot}})}{(Y-1)^2}
\end{aligned}$$

E | Script to plot the system temperature per zenith angle for all observations.

```
#!/usr/bin/env python
# -*- coding: utf-8 -*-

from __future__ import division
from matplotlib.pyplot import figure, show
from matplotlib.pyplot import *

import matplotlib.pyplot as plt
import numpy as np
import os
#-----------------------------------------------------------
''' Importing definitions to reduce the data coming from the telescope '''

def sec(z):
    return (1/ np.cos(z))

def tau_atm(z, tau_0):
    tau =tau_0 * sec(z)
    return tau

def Power(P_sys):
    P = (10**(P_sys/10))
    return P

def Yfac(P_hot, P_cold):
    y = 10**((P_hot-P_cold)/10)
    return y

def T_e(Y, T_hot, T_cold):
    t = (T_hot-T_cold*Y)/(Y-1)
    return t

def Gain(Phot, Pcold, T_hot, T_cold):
    G = (((Phot-Pcold)*10**-3 )/(T_hot-T_cold)) /(k*dv)
    return G

def Temp(P_sys, G):
    T = (P_sys*10**-3) / (G * k * dv)
    return T

#-----------------------------------------------------------
''' Correction for the calibration '''

def T_correction(P_hotsys, P_coldsys, P_hothand, P_coldhand, T_hot, T_coldhand):
    Y_hand = 10**((P_hothand-P_coldhand)/10)
    print 'The Y-factor for the measurements done by hand is:', Y_hand
    Y_sys = 10**((P_hotsys-P_coldsys)/10)
    print 'The Y-factor for the measurements done by the system is:', Y_sys
    T_noise = (T_hot-T_coldhand*Y_hand)/(Y_hand-1)
    print 'The T_noise for the measurements done by hand is:', T_noise, 'K'
    T = -1 * (T_noise*(Y_sys-1) - T_hot)/Y_sys
    return T
```

```python
#-------------------------------------------------------------
''' The values for the knowns '''

Temp_hot = [307.1,307.5,308.1,307.7,306.4,306.4] #K These are the temperatures of the
    hot load for all observations made on 07-04-15
T_cold_real = 77.14 #K This is the real temperature of liquid nitrogen
P_cold_real = -23.7554554 #dBm If the telecope was calibrated correct, this was the
    incoming power achieved from measuring the cold load

k = 1.3807e-23 #JK^-1
dv = 1.05e9 #Hz Our telescope's bandwidth

#-------------------------------------------------------------
''' Start Program '''

print ''
print ' ---------------------------------------------------------------------- '
print ' Program to calculate the system power according to the incoming power '
print ' ---------------------------------------------------------------------- '

#-------------------------------------------------------------
''' Input of the data from the telescope '''

print '                             Data input                              '
print ' --------------------------------------------------------------------- '

data = []
for f in os.listdir('./'):
    skip = False
    if f.startswith('data') and f.endswith('.txt'):
        if 'hotcold' in f:
            print 'Ignoring ' + f + '[hot-cold measurement].'
            skip = True
        if 'atm' in f:
            print 'Ignoring ' + f + '[atmosphere measurement].'
            skip = True
        if skip:
            continue
        data.append(f)

i = 0
data = sorted(data, key=str.lower)
for dataset in data:
    zangle, outpower = np.loadtxt(dataset, unpack=True, usecols=(0,1), dtype=str)
    hour = dataset[4:6]
    minutes = dataset[6:8]

    print 'These are the plots consering the data taken at %s:%s' %(hour, minutes)

    #-------------------------------------------------------------
    ''' Calculating System power on every angle '''

    angle = np.array([float(x) for x in zangle])
    angle = angle - 90
    power = np.array([float(x) for x in outpower])
    Photreal = power[1]
    Photsys = power[1]
    Pcoldsys = power[0]

    T_hot = Temp_hot[i]

    #-------------------------------------------------------------
```

```python
''' Calculating System temperature on every angle '''

T_coldsys = T_correction(Photsys, Pcoldsys, Photreal, P_cold_real, T_hot,
    T_cold_real)

gainreal = Gain(Power(Photsys),Power(Pcoldsys), T_hot, T_cold_real)
gainsys = Gain(Power(Photsys),Power(Pcoldsys), T_hot, T_coldsys)

temperature = Temp(Power(power), gainsys)

Yfactor_system = Yfac(power[1],power[0])
Yfactor_cold = Yfac(power[1],-23.7554554)
temp_rec = T_e(Yfactor_system, T_hot, T_coldsys)

print 'With the system, we look at a cold load having a temperature of ', T_coldsys,
    'K'
print 'According to the measurements, the system Gain equals ', 10*np.log10(gainsys)
    , 'dB'

#------------------------------------------------------------
''' Creating plots for the Power and the System temperature '''

print '                    Creating plot from measurements                    '
print ' -------------------------------------------------------------------- '
fig1 = figure(figsize=(14,5))
fig1.suptitle('Observation of the sky, 07-04-15, %s:%s' %(hour, minutes))

frame = fig1.add_subplot(1,2,1)
frame.set_title('Power (dBm) on the sky', fontsize='10')
frame.plot(angle[2:], power[2:], 'g', label='Power (dBm) per angle ($\\degree$)')
plt.xlabel('Zenith angle $\\degree$')
plt.ylabel('Power (dBm)')

frame = fig1.add_subplot(1,2,2)
frame.set_title('System temperature on the sky', fontsize='10')
frame.plot(angle[2:], temperature[2:], 'b', label='System temperature $T_{sys}$')
plt.axhline(y=temp_rec, color='r', linestyle='--', label='Receiver temperature $T_{
    rx}$')
plt.text(10, temp_rec+3, '$T_{rx}$= %d K' %(temp_rec), color='r')
lgd = frame.legend(loc="upper left", bbox_to_anchor=(0,1))
plt.xlabel('Zenith angle $\\degree$')
plt.ylabel('System Tenperature (K)')

fig1.savefig('data_07-04-15_%s%s-goodcalib.png' %(hour, minutes) ,
    bbox_extra_artists=(lgd,) )#, bbox_inches='tight')
i = i+1
```

F | Script to plot measurements of hot and cold load for measurements done by hand and for the horn placed in the system.

```
#!/usr/bin/env python
# -*- coding: utf-8 -*-

from __future__ import division
from matplotlib.pyplot import figure, show
from matplotlib.pyplot import *

import matplotlib.pyplot as plt
import numpy as np
import os
import math
#------------------------------------------------------------
''' Known values of the antenna '''

k = 1.3807e-23 #JK^-1
dv = 1.05e9 #Hz Our telescope's bandwidth

''' Definitions used '''

def Power(P_sys):
    P = (10**(P_sys/10))
    return P

def Yfac(P_hot, P_cold):
    y = 10**((P_hot-P_cold)/10)
    return y

def Gain(P_hot, P_cold, T_hot, T_cold):
    G = (((P_hot-P_cold)*10**-3 )/(T_hot-T_cold)) /(k*dv)
    return G

def T_correction(P_hotsys, P_coldsys, P_hothand, P_coldhand, T_hot, T_coldhand):
    Y_hand = 10**((P_hothand-P_coldhand)/10)
    print 'The Y-factor for the measurements done by hand is:', Y_hand
    Y_sys = 10**((P_hotsys-P_coldsys)/10)
    print 'The Y-factor for the measurements done by the system is:', Y_sys
    T_noise = (T_hot-T_coldhand*Y_hand)/(Y_hand-1)
    print 'The T_noise for the measurements done by hand is:', T_noise, 'K'
    T = -1 * (T_noise*(Y_sys-1) - T_hot)/Y_sys
    return T

def T_e(Y, T_hot, T_cold):
    t = (T_hot-T_cold*Y)/(Y-1)
    return t
#------------------------------------------------------------
''' Start Program '''

print ''
print ' ----------------------------------------------------------------------- '
```

```
print '        Program to calculate all values usefull for calibration        '
print ' ---------------------------------------------------------------------- '

#--------------------------------------------------------------
''' Input of the data from the telescope for system measurements '''

print '                         Data input system                         '
print ' --------------------------------------------------------------------- '

timeCold, syscold, timeHot, syshot, Hottemp, Atmtemp = np.loadtxt('data175249_hotcold.
    txt', unpack=True, usecols=(0, 1, 2, 3, 4, 5))

Atmtemp = np.array([float(x) for x in Atmtemp])
Hottemp = np.array([float(x) for x in Hottemp])
syscold = np.array([float(x) for x in syscold])
syshot = np.array([float(x) for x in syshot])
timeHot = np.array([float(x) for x in timeHot])- float(timeHot[0])
timeCold = np.array([float(x) for x in timeCold])- float(timeCold[0])

#--------------------------------------------------------------
''' Creating a power plot for the Hot Cold load measurements done with the horn placed
    in the frame for the telescope '''

print '                   Creating plot from measurements                   '
print ' --------------------------------------------------------------------- '
fig1 = figure(figsize=(14,5))
fig1.suptitle('Hotload and Coldload Measurement in system, 07-06-15, 17:52')

frame = fig1.add_subplot(1,2,1)
frame.plot(timeHot, Power(syshot), 'b', label='Hotload')
frame.plot(timeCold, Power(syscold), 'r', label='Coldload')
frame.set_title('Power per angle in mW', fontsize='10')
plt.ticklabel_format(style='sci', axis='y', scilimits=(0,0))
plt.xlabel('Time (s)')
plt.ylabel('Power (mW)')

frame = fig1.add_subplot(1,2,2)
frame.plot(timeHot, syshot, 'b', label='Hotload')
frame.plot(timeCold, syscold, 'r', label='Coldload')
frame.set_title('Power per angle in dBm', fontsize='10')
lgd = frame.legend(loc="upper left", bbox_to_anchor=(0.05,0.90))
plt.xlabel('Time (s)')
plt.ylabel('Power (dBm)')

show()
fig1.savefig('data_07-06-15_1752_HCsystem.png', bbox_extra_artists=(lgd,))

''' Our fixed calibration values '''
T_cold_real = 77.14 #K This is the real temperature of liquid nitrogen
P_cold_real = -23.7554554 #dBm If the telecope was calibrated correct, this was the
    incoming power achieved from measuring the cold load

#--------------------------------------------------------------
''' Calculating all values we want to know from the calibration set-up '''

aversyshot = np.mean(syshot)
aversyscold = np.mean(syscold)
averHottemp = np.mean(Hottemp)
averColdtemphand = T_cold_real

averATMtemp = np.mean(Atmtemp)

averColdload = P_cold_real
```

```
Tcoldsys = T_correction(aversyshot, aversyscold, aversyshot, averColdload, averHottemp,
    averColdtemphand)

gainreal = Gain(Power(aversyshot),Power(P_cold_real), averHottemp, T_cold_real)
gainsys = Gain(Power(aversyshot), Power(averColdload), averHottemp, Tcoldsys)

Yfactor_system = Yfac(aversyshot,aversyscold)
Yfactor_cold = Yfac(aversyshot,P_cold_real)

#------------------------------------------------------------
''' Printing all values from the measurement '''

print 'In the system we look at a coldload of about', Tcoldsys, 'K'
print 'According to the calculations we have a System Gain of', 10 * np.log10(gainsys),
    'dB'
print 'The receiver temperature of the system becomes', T_e(Yfactor_system, averHottemp,
     Tcoldsys), 'K'
print 'The average Phot of the system =', aversyshot, 'dBm'
print 'The average Pcold of the system =', aversyscold, 'dBm'
print 'The average Hotload temperature measured by the system equals', averHottemp, 'K'
print 'The average Atmospheric temperature has a value of', averATMtemp, 'K'

#------------------------------------------------------------
''' Input of the data from the telescope for manual measurements '''

print '                         Data input manual                              '
print ' ------------------------------------------------------------------- '

data = []
for f in os.listdir('./'):
    skip = False
    if f.startswith('data') and f.endswith('.txt'):
        if 'hotcold' in f:
            print 'Ignoring ' + f + '[hot-cold measurement].'
            skip = True
        if 'atm' in f:
            print 'Ignoring ' + f + '[atmosphere measurement].'
            skip = True
        if 'cmb' in f:
            print 'Ignoring ' + f + '[cmb measurement].'
            skip = True
        if skip:
            continue
        data.append(f)

data = sorted(data, key=str.lower)
for dataset in data:
    timepower, outpower= np.loadtxt(dataset, unpack=True, usecols=(0, 1))
    hour = dataset[4:6]
    minutes = dataset[6:8]

    Hotload = []
    timeHot = []
    Coldload = []
    timeCold = []

    for i in range(len(outpower)):
        if outpower[i] > -21.0:
            Hotload.append(outpower[i])
            timeHot.append(timepower[i])
        elif -21.15 >= outpower[i] >= -23.3:
            pass
```

```python
    elif outpower[i] < -23.3:
        Coldload.append(outpower[i])
        timeCold.append(timepower[i])

#------------------------------------------------------------
''' Calculating all values we want to know from the calibration manual measurements
    '''

aversyshot = np.mean(Hotload)
aversyscold = np.mean(Coldload)
averHottemp = 298.97

averColdtemphand = T_cold_real
averATMtemp = 296.6
averColdload = P_cold_real

Tcoldsys = T_correction(aversyshot, aversyscold, aversyshot, averColdload,
    averHottemp, averColdtemphand)

gainreal = Gain(Power(aversyshot),Power(P_cold_real), averHottemp, T_cold_real)
gainsys = Gain(Power(aversyshot), Power(averColdload), averHottemp, Tcoldsys)

Yfactor_system = Yfac(aversyshot,aversyscold)
Yfactor_cold = Yfac(aversyshot,P_cold_real)

#------------------------------------------------------------
''' Printing all values from the measurement '''

print 'These values are obtained by the use of data:', dataset
print 'In the system we look at a coldload of about', Tcoldsys, 'K'
print 'According to the calculations we have a System Gain of', 10 * np.log10(
    gainsys), 'dB'
```

G | Script to get τ_0 and T_{excess} from observations.

```
#!/usr/bin/env python
# -*- coding: utf-8 -*-

from __future__ import division
from matplotlib.pyplot import figure, show
from matplotlib.pyplot import *

from scipy.optimize import curve_fit
import matplotlib.pyplot as plt
import numpy as np

import os
#-----------------------------------------------------------
''' Importing definitions to reduce the data coming from the telescope '''

def sec(z):
    return (1/ np.cos(z))

def tau_atm(z, tau_0):
    tau =tau_0 * sec(z)
    return tau

def Power(Psys):
    P = (10**(Psys/10))
    return P

def Yfac(Ph, Pc):
    y = 10**((Ph-Pc)/10)
    return y

def T_e(Y, T_hot, T_cold):
    t = (T_hot-T_cold*Y)/(Y-1)
    return t

def T_correction(P_hsys, P_csys, P_hhand, P_chand, Th, T_chand):
    Y_h = 10**((P_hhand-P_chand)/10)
    Y_s = 10**((P_hsys-P_csys)/10)
    T_noise = (Th-T_chand*Y_h)/(Y_h-1)
    T_cc = -1 * (T_noise*(Y_s-1) - Th)/Y_s
    return T_cc

def Gain(Ph, Pc, Th, Tc):
    G = (((Ph-Pc)*10**-3 )/(Th-Tc)) /(k*dv)
    return G

def Temp(P_sys, G):
    T = (P_sys*10**-3) / (G * k * dv)
    return T
#-----------------------------------------------------------
''' Definitions of for error calculations '''

def erP():
    unc = 0.02 / ((N)**(0.5))
    return unc
```

```
def errorY(Ph, Pc):
    erPc, erPh = erP(), erP()
    difPh = (np.log(10) *(10**((Ph - Pc-10)/10)))**2
    difPc = (np.log(10) *(-10**((Ph - Pc-10)/10)))**2
    error = (difPh * erPh**2 + difPc * erPc**2)**(1/2)
    return error

def errorT_rec(Y, Th, Tc, Ph, Pc):
    erTh = erT(Th)
    erTc = erT(Tc)
    difTh = (1 / (Y-1))**2
    difTc = (-Y / (Y-1))**2
    difY = ((Tc-Th)/ ((Y-1)**2))**2
    erY = errorY(Ph, Pc)
    error = (difTh * erTh**2 + difTc * erTc**2 + difY * erY**2)**(1/2)
    return error

def erT(T):
    t = (0.6 + 0.005*(T-273.15)) / ((N)**(0.5))
    return t
#------------------------------------------------------------
''' Calculating the derivatives in order to calculate the uncertainty '''

# Derivative in T_cmb
def derT_cmb(tau):
    d = (np.exp(- tau))
    return d**2

# Derivative in T_atm
def derT_atm(tau):
    d = (1 - np.exp(- tau))
    return d**2

# Derivative in T_rec
def derT_rec():
    d = 1
    return d**2

# Derivative in tau
def dertau(tau):
    d = ((T_atm-T_cmb)*np.exp(- tau))
    return d**2

# Uncertainty in T_sys
def uncertT_sys(z, Y, Th, Tc, Ph, Pc):
    derTcmb = derT_cmb(tau_atm(z, tau_0))
    derTau = dertau(tau_atm(z, tau_0))
    derTrec = derT_rec()
    derTatm = derT_atm(tau_atm(z, tau_0))
    unTatm = erT(T_atm)
    unTcmb = (0.00057)/((N)**(0.5)) # Uncertainty in T_cmb according to the literature
    unTau = (0.005)/((N)**(0.5)) # I estimated a fluctuation in the opacity of 0.005 as
        'worst case scenario'
    unTrec = errorT_rec(Y, Th, Tc, Ph, Pc)
    u = ( ((derTcmb)* unTcmb**2 ) + ((derTatm)* unTatm**2 ) + ((derTau)* unTau**2 ) + ((
        derTrec)* unTrec**2)) **(1/2)
    return u
#------------------------------------------------------------
''' The values for the knowns '''

T_cmb = 2.73 #K
Temp_hot = [295.35,295.02,294.64] #K These are the temperatures of the hot load for all
    observations made on 07-10-15
```

```
T_cold_real = 77.14 #K This is the real temperature of liquid nitrogen
P_cold_real = -23.7554554 #dBm If the telecope was calibrated correct, this was the
    incoming power achieved from measuring the cold load

Temp_atm = [293.15,293.17,293.0] #K These are the temperatures of the atmosphere for all
     observations made on 07-10-15

k = 1.3807e-23 #JK^-1
dv = 1.05e9 #Hz Our telescope's bandwidth

N = 256 # The amount of measurements made per angle

#------------------------------------------------------------
''' Start Program '''

print ''
print ' ------------------------------------------------------------------- '
print ' Program to calculate the system power according to the incoming power '
print ' ------------------------------------------------------------------- '

#------------------------------------------------------------
''' Input of the data from the telescope '''

print '                            Data input                              '
print ' ------------------------------------------------------------------ '

data = []
for f in os.listdir('./'):
    skip = False
    if f.startswith('data') and f.endswith('.txt'):
        if 'hotcold' in f:
            print 'Ignoring ' + f + '[hot-cold measurement].'
            skip = True
        if 'atm' in f:
            print 'Ignoring ' + f + '[atmosphere measurement].'
            skip = True
        if 'cmb' in f:
            print 'Ignoring ' + f + '[cmb measurement].'
            skip = True
        if skip:
            continue
        data.append(f)

i = 0
data = sorted(data, key=str.lower)
for dataset in data:
    zangle, outpower = np.loadtxt(dataset, unpack=True, usecols=(0,1), dtype=str)
    hour = dataset[4:6]
    minutes = dataset[6:8]

    print 'These are the values conserning the data taken at %s:%s' %(hour, minutes)

    #------------------------------------------------------------
    ''' Calculating System power on every angle '''

    angle = np.array([float(x) for x in zangle])
    angle = angle - 90
    power = np.array([float(x) for x in outpower])

    Photreal = power[1]
    Photsys = power[1]
    Pcoldsys = power[0]
```

```python
T_hot = Temp_hot[i]
T_atm = Temp_atm[i]


T_coldsys = T_correction(Photsys, Pcoldsys, Photreal, P_cold_real, T_hot,
    T_cold_real)

gainreal = Gain(Power(Photsys),Power(Pcoldsys), T_hot, T_cold_real)
gainsys = Gain(Power(Photsys),Power(Pcoldsys), T_hot, T_coldsys)

temperature = Temp(Power(power), gainsys)

Yfactor_system = Yfac(power[1],power[0])
Yfactor_cold = Yfac(power[1],-23.7554554)
temp_rec = T_e(Yfactor_system, T_hot, T_coldsys)

print 'With the system, we look at a cold load having a temperature of ', T_coldsys,
     'K'
print 'According to the measurements, the system Gain equals ', 10*np.log10(gainsys)
    , 'dB'


#------------------------------------------------------------
''' Plotting the data for the power and system temperature per angle '''

print '                   Creating plot from measurements                    '
print ' -----------------------------------------------------------------  '
fig = figure(figsize=(12,5))
fig.suptitle('Observation of the sky, looking for $\\tau_0$, 07-10-15, %s:%s' %(hour
    , minutes), fontsize='14')

frame = fig.add_subplot(1,2,1)
frame.plot(angle[2:], power[2:])
frame.set_title('Power per angle in mdB', fontsize='12')
plt.xlabel('Zenith angle $\\degree$')
plt.ylabel('Power (mdB)')

#------------------------------------------------------------
''' Determining the value for the gainfactor and temperatures '''
temperature = Temp(Power(power), gainsys)

frame = fig.add_subplot(1,2,2)
frame.set_title('System temperature on the sky', fontsize='12')
frame.plot(angle[2:], temperature[2:], 'b', label='System temperature $T_{sys}$')
plt.axhline(y=temp_rec, color='r', linestyle='--', label='Receiver temperature $T_{
    rx}$')
plt.text(10, temp_rec+3, '$T_{rx}$= %d K' %(temp_rec), color='r')
lgd = frame.legend(loc="upper left", bbox_to_anchor=(0,1))
plt.xlabel('Zenith angle $\\degree$')
plt.ylabel('System Tenperature (K)')

fig.savefig('data_07-10-15_%s%s-good.png' %(hour, minutes), bbox_extra_artists=(lgd
    ,) )

#------------------------------------------------------------
''' Determining the value for the opacity '''

def func(z, tau_0):
    return ( T_cmb * np.exp(- tau_atm(z, tau_0)) ) + ( T_atm * (1 - np.exp(- tau_atm
        (z, tau_0))) + temp_rec )

popt, pcov = curve_fit(func, np.radians(angle[2:]), temperature[2:])
```

```
print 'The value for the opacity is', popt[0]
tau_0 = popt[0]

unT_rec = errorT_rec( Yfactor_system, T_hot, T_coldsys, power[1], power[0])
unT_sys = np.mean(uncertT_sys(angle[2:], Yfactor_system, T_hot, T_coldsys, power[1],
     power[0]))

popt, pcov = curve_fit(func, np.radians(angle[2:]), temperature[2:], sigma=(unT_sys*
    np.ones(len(temperature[2:]))), absolute_sigma= True)

print 'The uncertainty in our receiver temperature is', unT_rec, 'K'
print 'and therefore, the uncertainty in our system temperature becomes', unT_sys, '
    K'
print 'The error in the fit for tau_0 equals', (pcov[0,0])**(0.5)

#--------------------------------------------------------------
''' Determining the temperature of the CMB as antenna excess temperature '''

subtr = (temperature - temp_rec - (T_atm)*(1-np.exp(-tau_0 * sec(np.radians(angle)))
    ) )

fig = figure()
fig.suptitle('An excess antenna temperature on the sky, 07-10-15, %s:%s' %(hour,
    minutes), fontsize='14')

frame = fig.add_subplot(1,1,1)
frame.plot(angle[2:], subtr[2:], 'b', label='Axcess antenna temperature?')
#lgd = frame.legend(loc="upper left", bbox_to_anchor=(0,1))
plt.xlabel('Zenith angle $\\degree$')
plt.ylabel('System Tenperature (K)')
frame.set_ylim(0,25)
show()

fig.savefig('excesstemp_07-10-15_%s%s.png' %(hour, minutes),)
```

H Script to get τ_0 and $T_{\rm cmb}$ from observations.

```python
#!/usr/bin/env python
# -*- coding: utf-8 -*-

from __future__ import division
from matplotlib.pyplot import figure, show
from matplotlib.pyplot import *

from scipy.optimize import curve_fit
import matplotlib.pyplot as plt
import numpy as np

import os
#-----------------------------------------------------------
''' Importing definitions to reduce the data coming from the telescope '''

def sec(z):
    return (1/ np.cos(z))

def tau_atm(z, tau_0):
    tau =tau_0 * sec(z)
    return tau

def Power(Psys):
    P = (10**(Psys/10))
    return P

def Yfac(Ph, Pc):
    y = 10**((Ph-Pc)/10)
    return y

def T_e(Y, T_hot, T_cold):
    t = (T_hot-T_cold*Y)/(Y-1)
    return t

def T_correction(P_hsys, P_csys, P_hhand, P_chand, Th, T_chand):
    Y_h = 10**((P_hhand-P_chand)/10)
    Y_s = 10**((P_hsys-P_csys)/10)
    T_noise = (Th-T_chand*Y_h)/(Y_h-1)
    T_cc = -1 * (T_noise*(Y_s-1) - Th)/Y_s
    return T_cc

def Gain(Ph, Pc, Th, Tc):
    G = (((Ph-Pc)*10**-3 )/(Th-Tc)) /(k*dv)
    return G

def Temp(P_sys, G):
    T = (P_sys*10**-3) / (G * k * dv)
    return T
#-----------------------------------------------------------
''' Definitions of for error calculations '''

def erP():
    unc = 0.02 / ((N)**(0.5))
    return unc
```

```python
def errorY(Ph, Pc):
    erPc, erPh = erP(), erP()
    difPh = (np.log(10) *(10**((Ph - Pc-10)/10)))**2
    difPc = (np.log(10) *(-10**((Ph - Pc-10)/10)))**2
    error = (difPh * erPh**2 + difPc * erPc**2)**(1/2)
    return error

def errorT_rec(Y, Th, Tc, Ph, Pc):
    erTh = erT(Th)
    erTc = erT(Tc)
    difTh = (1 / (Y-1))**2
    difTc = (-Y / (Y-1))**2
    difY = ((Tc-Th)/ ((Y-1)**2))**2
    erY = errorY(Ph, Pc)
    error = (difTh * erTh**2 + difTc * erTc**2 + difY * erY**2)**(1/2)
    return error

def erT(T):
    t = (0.6 + 0.005*(T-273.15)) / ((N)**(0.5))
    return t
#---------------------------------------------------------------
''' Calculating the derivatives in order to calculate the uncertainty '''

# Derivative in T_cmb
def derT_cmb(tau):
    d = (np.exp(- tau))
    return d**2

# Derivative in T_atm
def derT_atm(tau):
    d = (1 - np.exp(- tau))
    return d**2

# Derivative in T_rec
def derT_rec():
    d = 1
    return d**2

# Derivative in tau
def dertau(tau):
    d = ((T_atm-T_cmb)*np.exp(- tau))
    return d**2

# Uncertainty in T_sys
def uncertT_sys(z, Y, Th, Tc, Ph, Pc):
    derTcmb = derT_cmb(tau_atm(z, tau_0))
    derTau = dertau(tau_atm(z, tau_0))
    derTrec = derT_rec()
    derTatm = derT_atm(tau_atm(z, tau_0))
    unTatm = erT(T_atm)
    unTcmb = (0.00057)/((N)**(0.5)) # Uncertainty in T_cmb according to the literature
    unTau = (0.005)/((N)**(0.5)) # I estimated a fluctuation in the opacity of 0.005 as
        'worst case scenario'
    unTrec = errorT_rec(Y, Th, Tc, Ph, Pc)
    u = ( ((derTcmb)* unTcmb**2 ) + ((derTatm)* unTatm**2 ) + ((derTau)* unTau**2 ) + ((
        derTrec)* unTrec**2)) **(1/2)
    return u
#---------------------------------------------------------------
''' The values for the knowns '''

T_hot = 295.10 #K This is the temperature of the hot load during the observation on
    07-10-15 at 13:28
T_cold_real = 77.14 #K This is the real temperature of liquid nitrogen
```

```
P_cold_real = -23.7554554 #dBm If the telecope was calibrated correct, this was the
    incoming power achieved from measuring the cold load

T_atm = 293.82 #K This is the temperatures of the atmosphere for the observations on
    07-10-15 at 13:28

k = 1.3807e-23 #JK^-1
dv = 1.05e9 #Hz Our telescope's bandwidth

N = 256 # The amount of measurements made per angle

#-------------------------------------------------------------
''' Start Program '''

print ''
print ' ---------------------------------------------------------------------- '
print ' Program to calculate the system power according to the incoming power '
print ' ---------------------------------------------------------------------- '

#-------------------------------------------------------------
''' Input of the data from the telescope '''

print '                              Data input                              '
print ' --------------------------------------------------------------------- '
zangle, outpower = np.loadtxt("data132804_cmb.txt", unpack=True, usecols=(0,1), dtype=
    str)

#-------------------------------------------------------------
''' Calculating System power on every angle '''

angle = np.array([float(x) for x in zangle])
angle = angle - 90
power = np.array([float(x) for x in outpower])

Photreal = power[1]
Photsys = power[1]
Pcoldsys = power[0]

T_coldsys = T_correction(Photsys, Pcoldsys, Photreal, P_cold_real, T_hot, T_cold_real)

gainreal = Gain(Power(Photsys),Power(Pcoldsys), T_hot, T_cold_real)
gainsys = Gain(Power(Photsys),Power(Pcoldsys), T_hot, T_coldsys)

temperature = Temp(Power(power), gainsys)

Yfactor_system = Yfac(power[1],power[0])
Yfactor_cold = Yfac(power[1],-23.7554554)
temp_rec = T_e(Yfactor_system, T_hot, T_coldsys)

print 'With the system, we look at a cold load having a temperature of ', T_coldsys, 'K'
print 'According to the measurements, the system Gain equals ', 10*np.log10(gainsys), '
    dB'


print '                    Creating plot from measurements                    '
print ' --------------------------------------------------------------------- '
fig = figure(figsize=(17,5))
fig.suptitle('Observation of the sky, looking for $T_{cmb}$, 07-10-15, 13:28', fontsize=
    '14')

frame = fig.add_subplot(1,3,1)
frame.plot(angle[2:], power[2:])
frame.set_title('Power per angle in mdB', fontsize='12')
```

```
plt.xlabel('Zenith angle $\\degree$')
plt.ylabel('Power (mdB)')

#-----------------------------------------------------------
''' Determining the value for the gainfactor and temperatures '''
temperature = Temp(Power(power), gainsys)

frame = fig.add_subplot(1,3,2)
frame.set_title('System temperature on the sky', fontsize='12')
frame.plot(angle[2:], temperature[2:], 'b', label='System temperature $T_{sys}$')
plt.axhline(y=temp_rec, color='r', linestyle='--', label='Receiver temperature $T_{rx}$'
    )
plt.text(10, temp_rec+3, '$T_{rx}$= %d K' %(temp_rec), color='r')
lgd = frame.legend(loc="upper left", bbox_to_anchor=(0,1))
plt.xlabel('Zenith angle $\\degree$')
plt.ylabel('System Tenperature (K)')

#-----------------------------------------------------------
''' Determining the value for the opacity and T_cmb '''

def func(z, tau_0, T_cmb):
    return ( T_cmb * np.exp(- tau_atm(z, tau_0)) ) + ( T_atm * (1 - np.exp(- tau_atm(z,
        tau_0))) + temp_rec )

popt, pcov = curve_fit(func, np.radians(angle[2:]), temperature[2:])

print 'The value for the opacity is', popt[0]
print 'The value for the temperature of the CMB is', popt[1], 'K'

tau_0 = popt[0]
T_cmb = popt[1]

popt, pcov = curve_fit(func, np.radians(angle[2:]), temperature[2:])

unT_rec = errorT_rec( Yfactor_system, T_hot, T_coldsys, power[1], power[0])
unT_sys = np.mean(uncertT_sys(angle[2:], Yfactor_system, T_hot, T_coldsys, power[1],
    power[0]))

popt, pcov = curve_fit(func, np.radians(angle[2:]), temperature[2:], sigma=(unT_sys*np.
    ones(len(temperature[2:]))), absolute_sigma= True)

print 'The uncertainty in our receiver temperature is', unT_rec, 'K'
print 'and therefore, the uncertainty in our system temperature becomes', unT_sys, 'K'
print 'The error in the fit for tau_0 equals', (pcov[0,0])**(0.5)

#-----------------------------------------------------------
''' Plotting a funtion for the system temperature according to the fit made with
    curve_fit '''

hoek = np.radians(np.linspace(0,90,1000))

frame = fig.add_subplot(1,3,3)
frame.plot(angle[2:], temperature[2:])
frame.plot(np.degrees(hoek),func(hoek,popt[0], popt[1]))
frame.set_title('System Temperature per angle in K', fontsize='10')
plt.xlabel('Angle $\\degree$')
plt.ylabel('Temperature (K)')

fig.savefig('data_07-10-15_1328-good.png', bbox_extra_artists=(lgd,) )
```

I | Script for Data Reduction and Calculations concerning correction for the Hot-Cold load Calibration.

```
#!/usr/bin/env python
# -*- coding: utf-8 -*-

from __future__ import division
from matplotlib.pyplot import figure, show
from matplotlib.pyplot import *

import matplotlib.pyplot as plt
import numpy as np
import os
import math
#--------------------------------------------------------------
''' Known values of the antenna '''

k = 1.3807e-23 #JK^-1
dv = 1.05e9 #Hz
T_cold = 77.14 #K

#--------------------------------------------------------------
''' Definitions used to calculate the 'real temperature' of our cold load '''

def Power(P_sys):
    P = (10**(P_sys/10))
    return P

def Gain(P_hot, P_cold):
    G = (((P_hot-P_cold)*10**-3 )/(T_hot-T_cold)) /(k*dv)
    G = 10* np.log10(G)
    return G

def T_correction(P_hotsys, P_coldsys, P_hothand, P_coldhand, T_hot, T_coldhand):
    Y_hand = 10**((P_hothand-P_coldhand)/10)
    print 'The Y-factor for the measurements done by hand is:', Y_hand
    Y_sys = 10**((P_hotsys-P_coldsys)/10)
    print 'The Y-factor for the measurements done by the system is:', Y_sys
    T_noise = (T_hot-T_coldhand*Y_hand)/(Y_hand-1)
    print 'The T_noise for the measurements done by hand is:', T_noise, 'K'
    T = -1 * (T_noise*(Y_sys-1) - T_hot)/Y_sys
    return T

#--------------------------------------------------------------
''' Start Program '''

print ''
print ' ------------------------------------------------------------------ '
print ' Program to calculate the system power according to the incoming power '
print ' ------------------------------------------------------------------ '

#--------------------------------------------------------------
''' Input of the data from the telescope '''

print '                            Data input                             '
```

```
print ' ---------------------------------------------------------------- '

data = []
for f in os.listdir('./'):
    skip = False
    if f.startswith('data') and f.endswith('.txt'):
        if 'hotcold' in f:
            print 'Ignoring ' + f + '[hot-cold measurement].'
            skip = True
        if 'atm' in f:
            print 'Ignoring ' + f + '[atmosphere measurement].'
            skip = True
        if skip:
            continue
        data.append(f)

data = sorted(data, key=str.lower)
for dataset in data:
    none, syscold, none, syshot, Hottemp, Coldtemp = np.loadtxt('data153303_hotcold20.
        txt', unpack=True, usecols=(0, 1, 2, 3, 4, 5))
    timepower, outpower= np.loadtxt(dataset, unpack=True, usecols=(0, 1), dtype=str)

    Hottemp = np.array([float(x) for x in Hottemp])
    syscold = np.array([float(x) for x in syscold])
    syshot = np.array([float(x) for x in syshot])

    timepower = np.array([float(x) for x in timepower])
    outpower = np.array([float(x) for x in outpower])

    #------------------------------------------------------------
    ''' Calculating System power on every angle '''

    Hotload = []
    timeHot = []
    Coldload = []
    timeCold = []

    for i in range(len(outpower)):
        if outpower[i] > -21.15:
            Hotload.append(outpower[i])
            timeHot.append(timepower[i])
        elif -21.15 <= outpower[i] <= -23.6:
            pass
        elif outpower[i] < -23.6:
            Coldload.append(outpower[i])
            timeCold.append(timepower[i])

    Hotload = np.array([float(x) for x in Hotload])
    timeHot = np.array([float(x) for x in timeHot])
    Coldload = np.array([float(x) for x in  Coldload])
    timeCold = np.array([float(x) for x in timeCold])

    aversyshot = np.mean(syshot)
    aversyscold = np.mean(syscold)
    averHottemp = np.mean(Hottemp)
    averColdtemphand = T_cold

    averHotload = np.mean(Hotload)
    averColdload = np.mean(Coldload)

    Tcoldsys = T_correction(aversyshot, aversyscold, averHotload, averColdload,
       averHottemp, averColdtemphand)
    print 'For the data concerning', dataset
```

```
print 'The average value for Phot and Pcold are', averHotload, 'dBm and ',
    averColdload, 'dBm respectively.'
print 'This will result in a temperature for our cold load being', Tcoldsys, 'K.'
```

J | Script to check for correlations between T_{cold} and T_{hot}.

```
#!/usr/bin/env python
# -*- coding: utf-8 -*-

from __future__ import division
from matplotlib.pyplot import figure, show
from matplotlib.pyplot import *

import matplotlib.pyplot as plt
import numpy as np
import os

from sympy import *
import scipy.optimize


#
    -----------------------------------------------------------------------------------------------

#
    -----------------------------------------------------------------------------------------------


T_cold_real = 77.15 #K
P_cold_real = -23.7554554 #dBm

k = 1.3807e-23 #JK^-1
dv = 1.05e9 #Hz


''' Start Program '''

print ''
print ' ---------------------------------------------------------------------------- '
print ' Program to look for correlations regarding the calibration of the telescope '
print ' ---------------------------------------------------------------------------- '

''' Input of the data from the telescope '''

print '                                 Data input                                  '
print ' ---------------------------------------------------------------------------- '

T_atm, T_hot, T_cold, P_hot, P_cold, T_rec, Gain, Sort= np.loadtxt('
    calabration_equationdata.txt', unpack=True, usecols=(0,1,2,3,4,5,6,7), dtype=str)
#Sort = Sort of measurement (1=daily, 2=hand, 3=sys)

T_atm = np.array([float(x) for x in T_atm])
T_hot = np.array([float(x) for x in T_hot])
T_cold = np.array([float(x) for x in T_cold])
P_hot = np.array([float(x) for x in P_hot])
P_cold = np.array([float(x) for x in P_cold])
T_rec = np.array([float(x) for x in T_rec])
Gain = np.array([float(x) for x in Gain])
Sort = np.array([float(x) for x in Sort])

def y(Tatm, Tcold):
```

```
    x = Symbol('x')
    return solve(( ( (1 - x) * T_cold_real) + (x * Tatm) - Tcold), x)

''' Plotting the dependence of the sort of measurement '''

print '                        Creating plot from measurements                        '
print ' ------------------------------------------------------------------------------ '
fig = figure(figsize=(14,5))
fig.suptitle('Dependence of sort of measurement on the cold load temperature T$_{cold}$'
    )

frame = fig.add_subplot(1,2,1)
frame.set_title('T$_{cold}$ vs. P$_{cold}$', fontsize='10')
frame.plot(T_cold, P_cold, 'black', marker='.', linestyle='', label='Power (dBm) per
    angle ($\\degree$)')
plt.xlabel('Temperature Cold Load (K)')
plt.ylabel('Power Cold Load (dBm)')

frame = fig.add_subplot(1,2,2)
frame.set_title('Looking for different measurements', fontsize='10')
T_1, T_2, T_3 = [], [], []
P_1, P_2, P_3 = [], [], []
for i in range(25):
    if Sort[i] == 1:
        T_1.append(T_cold[i])
        P_1.append(P_cold[i])
    elif Sort[i] == 2.:
        T_2.append(T_cold[i])
        P_2.append(P_cold[i])
    elif Sort[i] == 3.:
        T_3.append(T_cold[i])
        P_3.append(P_cold[i])

frame.plot(T_1, P_1, 'r', marker='.', linestyle='', label='Daily measurement')
frame.plot(T_2, P_2, 'b', marker='.', linestyle='', label='Manual measurement')
frame.plot(T_3, P_3, 'g', marker='.', linestyle='', label='System measurement')
lgd = frame.legend(loc="upper left", bbox_to_anchor=(0,1),numpoints=1)
plt.xlabel('Temperature Cold Load (K)')
plt.ylabel('Power Cold Load (dBm)')
fig.savefig('overall-equationcalibrationsort.png', bbox_extra_artists=(lgd,))

T_atm, T_hot, T_cold, P_hot, P_cold, T_rec, Gain, Sort= np.loadtxt('
    calabration_equationdatawithout.txt', unpack=True, usecols=(0,1,2,3,4,5,6,7), dtype=
    str)
#Sort = Sort of measurement (1=daily, 2=hand, 3=sys)

T_atm = np.array([float(x) for x in T_atm])
T_hot = np.array([float(x) for x in T_hot])
T_cold = np.array([float(x) for x in T_cold])
P_hot = np.array([float(x) for x in P_hot])
P_cold = np.array([float(x) for x in P_cold])
T_rec = np.array([float(x) for x in T_rec])
Gain = np.array([float(x) for x in Gain])
Sort = np.array([float(x) for x in Sort])

''' Plotting the T_atm dependence '''

print '                        Creating plot from measurements                        '
print ' ------------------------------------------------------------------------------ '
fig1 = figure(figsize=(7,7))
fig1.suptitle('Dependence of T$_{atm}$ on the cold load temperature T$_{cold}$')
frame = fig1.add_subplot(1,1,1)
frame.set_title('Looking for different T$_{atm}$', fontsize='10')
```

```
T_1, T_2, T_3, T_4 = [], [], [], []
P_1, P_2, P_3, P_4 = [], [], [], []
for j in range(23):
    if T_atm[j] <= 295:
        T_1.append(T_cold[j])
        P_1.append(P_cold[j])
    elif 295 < T_atm[j] < 300:
        T_2.append(T_cold[j])
        P_2.append(P_cold[j])
    elif 300 < T_atm[j] < 305:
        T_3.append(T_cold[j])
        P_3.append(P_cold[j])
    elif T_atm[j] >= 305:
        T_4.append(T_cold[j])
        P_4.append(P_cold[j])

frame.plot(T_1, P_1, 'g', marker='.', linestyle='', label='T$_{atm}$ < 295 K')
frame.plot(T_2, P_2, 'r', marker='.', linestyle='', label='295 K < T$_{atm}$ < 300 K')
frame.plot(T_3, P_3, 'b', marker='.', linestyle='', label='300 K < T$_{atm}$ < 305 K')
frame.plot(T_4, P_4, 'black', marker='.', linestyle='', label='T$_{atm}$ > 305 K')
lgd = frame.legend(loc="upper left", bbox_to_anchor=(0,1),numpoints=1)
plt.xlabel('Temperature Cold Load (K)')
plt.ylabel('Power Cold Load (dBm)')
fig1.savefig('overall-equationcalibrationTvsPtatmos.png', bbox_extra_artists=(lgd,))

''' Plotting the T_atm dependence '''

print '                         Creating plot from measurements                      '
print ' ----------------------------------------------------------------------------- '
fig2 = figure(figsize=(6.5,6.5))
fig2.suptitle('Dependence of T$_{atm}$ on the cold load temperature T$_{cold}$')

frame = fig2.add_subplot(1,1,1)
frame.set_title('T$_{atm}$ vs. P$_{cold}$', fontsize='10')
frame.plot(T_atm, P_cold, 'black', marker='.', linestyle='', label='Power (dBm) per
    angle ($\\degree$)')
plt.xlabel('Temperature Cold Load (K)')
plt.ylabel('Power Cold Load (dBm)')
fig2.savefig('overall-equationcalibrationTatmvsPtatmos.png', bbox_extra_artists=(lgd,))

''' Plotting the beam part falling out of the Cold Load  '''

print '                         Creating plot from measurements                      '
print ' ----------------------------------------------------------------------------- '
fig3 = figure(figsize=(6.5,6.5))
fig3.suptitle('Part of the beam falling out the cold load$')

frame = fig3.add_subplot(1,1,1)
frame.set_title('Using (1-x)*T$_{cold, real}$ + x*T$_{atm}$ = T$_{cold}$', fontsize='10'
    )
for i in range(23):
    solution = y(T_atm[i],T_cold[i])
    frame.plot(i, solution, 'black', marker='.', linestyle='')
plt.xlabel('Calibration measurements')
plt.ylabel('x (Part of the beam falling outside the coldload)')
fig3.savefig('overall-equationcalibrationbeamout.png')
```

K Logbook of all my observations with the telescope

See attached document.

Logbook observations

By Willeke Mulder

1 Observations 06-08-15

	Time	Observation of..	Measure size (°)	N [1]	T_{atm} (K)	P_{hot} (dBm)	P_{cold} (dBm) [2]	Gain (dB)	Description sky	Filename
1	13:00	CMB	6	1	—	—	—	—	A measurement is done while trying to avoid the Sun. Here we can see that the beam pattern shows side lobes in the horizontal direction. Therefore we get a signal of the Sun, while pointing next to the Sun. We have to check how much we have to move in order to not measure the Sun.	data1300.txt
2	13:02	Sun	6	1	—	—	—	—		data1302.txt
3	13:05	Sun	4	1	—	—	—	—		data1305.txt
4	13:08	Sun	1	1	—	—	—	—		data1308.txt
5	13:12	Sun with clouds	1	1	—	—	—	—	A observation while there are clouds on the sky.	data1312.txt

Table 1: Data from observations of the sky on 06-08-15

1.1 Sky observations

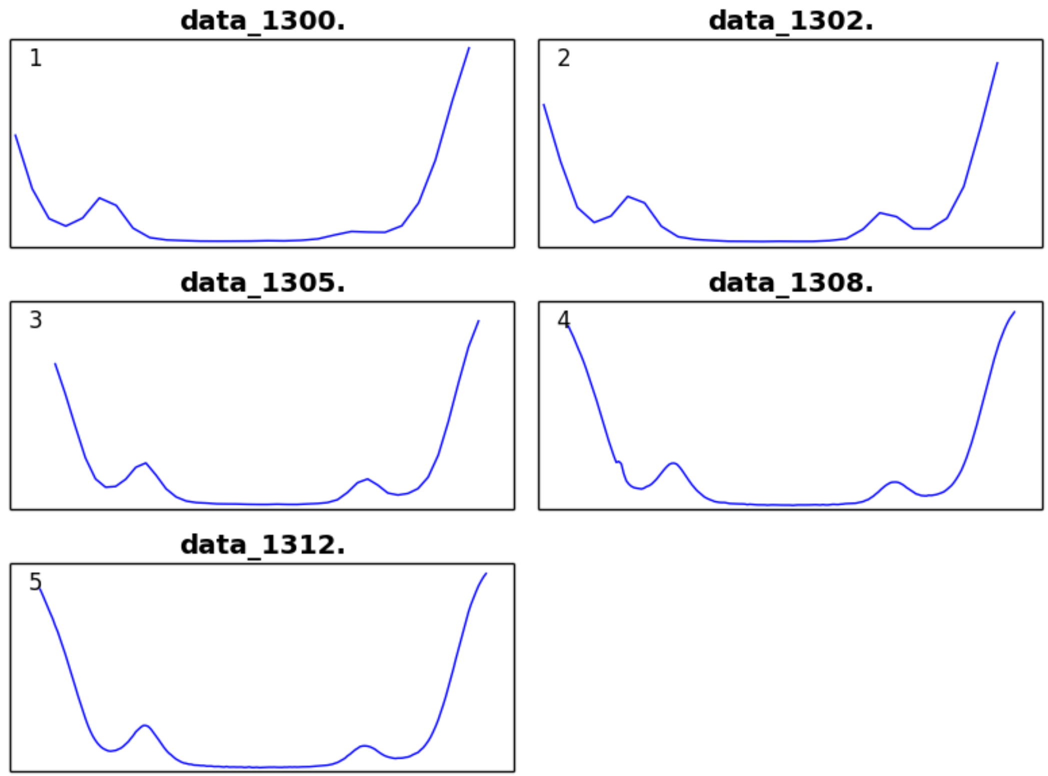
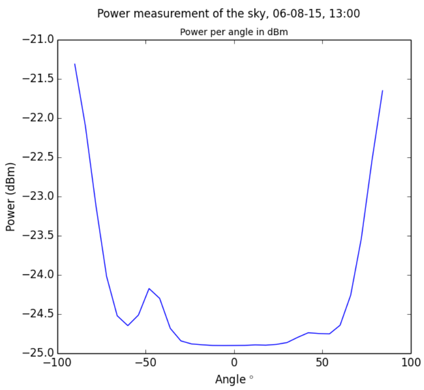


Figure 1: Overview measurements 06-08-2015.


Power measurement of the sky, 06-08-15, 13:00
Power per angle in dBm
Power (dBm)
Angle °

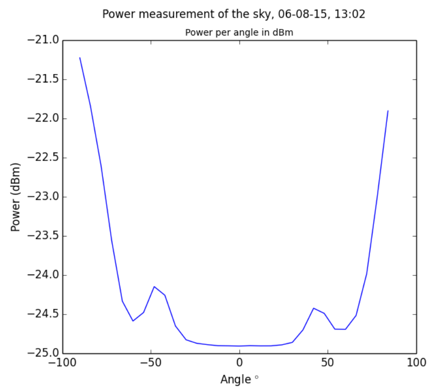
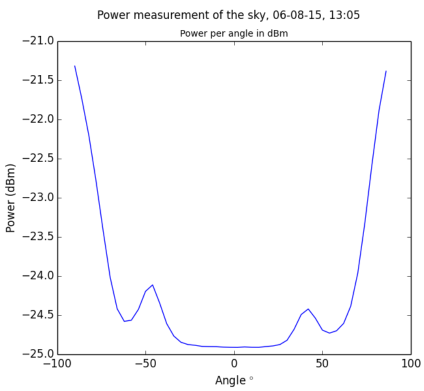
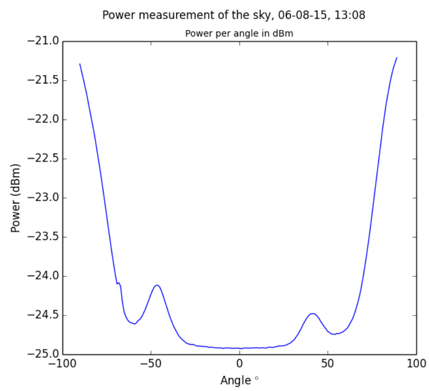
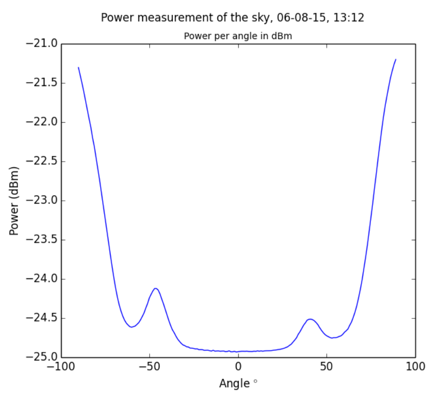

Power measurement of the sky, 06-08-15, 13:02
Power per angle in dBm
Power (dBm)
Angle °

Figure 2


Power measurement of the sky, 06-08-15, 13:05
Power per angle in dBm
Power (dBm)
Angle °


Power measurement of the sky, 06-08-15, 13:08
Power per angle in dBm
Power (dBm)
Angle °


Power measurement of the sky, 06-08-15, 13:12
Power per angle in dBm
Power (dBm)
Angle °

2 Observations 06-24-15

	Time	Observation of..	Measure size (°)	N [3]	T_{atm} (K)	P_{hot} (dBm)	P_{cold} (dBm) [4]	Gain (dB)	Description sky	Filename
1	11:21	Satellite	1	1	—	-20.94	-23.49	—		data112103.txt
2	11:22	Satellite	1	1	—	-20.94	-23.47	—		data112205.txt
3	11:24	Satellite	1	1	—	-20.96	-23.50	—		data112405.txt
4	11:24	Duisenberg	1	1	—	-20.81	-23.38	—		data112534.txt
5	11:26	Duisenberg	1	1	—	-20.78	-23.34	—		data112639.txt
6	11:30	Duisenberg	1	1	—	-20.91	-23.47	—		data113000.txt
7	11:33	Sun	1	1	—	-20.89	-23.49	—		data113334.txt
8	11:39	Sun	1	1	—	-20.89	-22.40	—		data113957.txt
9	11:48	Sun	1	1	—	-20.92	-22.53	—		data114853.txt

Table 2: Data from observations of the sky on 07-04-15

2.1 Sky observations

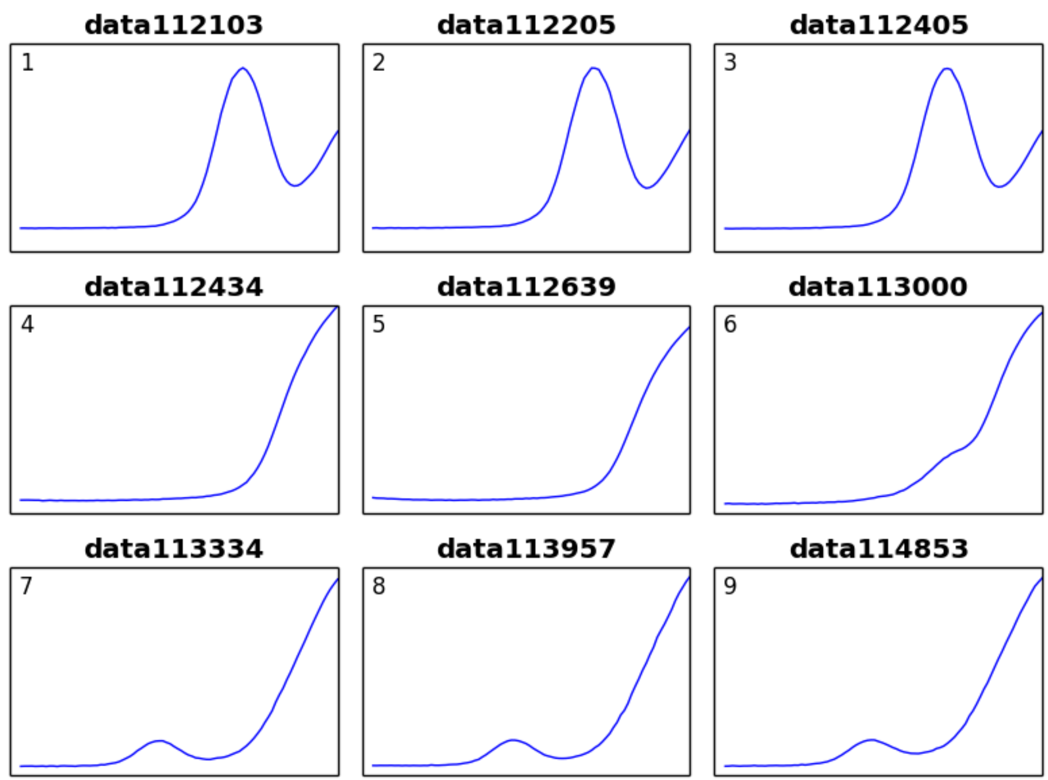
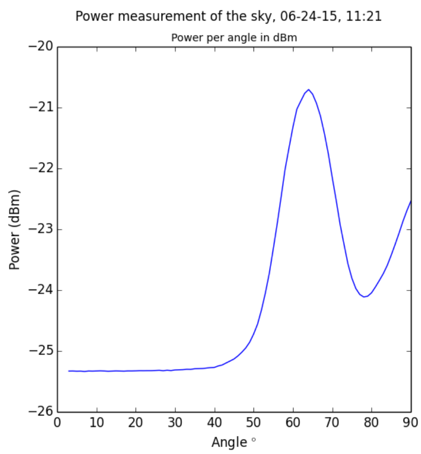
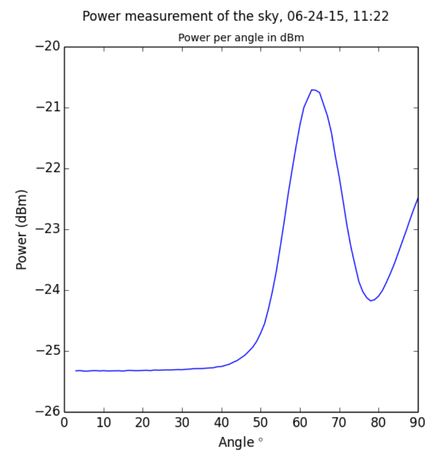
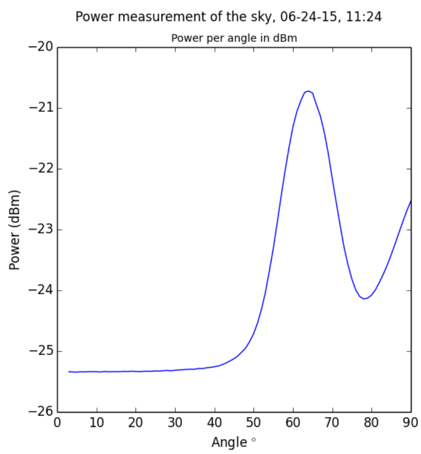
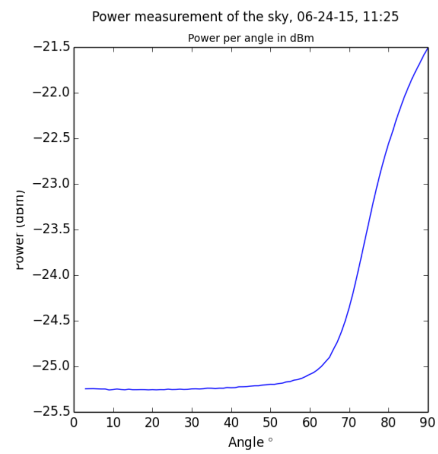


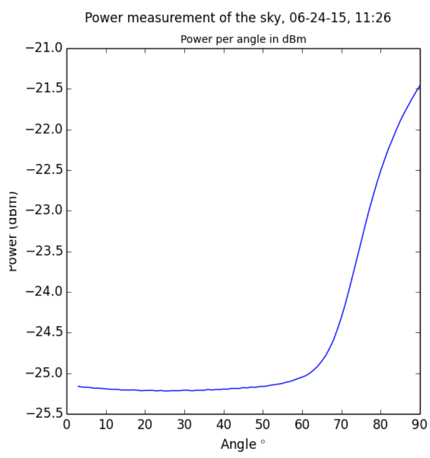
Figure 3: Overview measurements 06-24-2015.

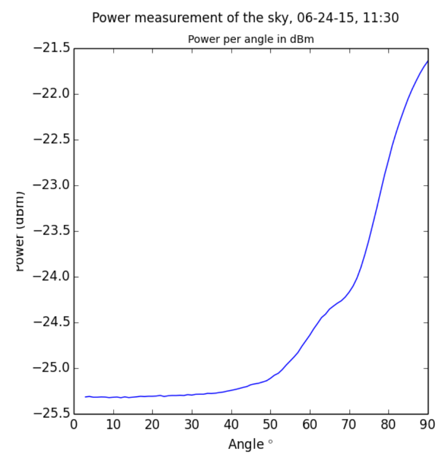

Power measurement of the sky, 06-24-15, 11:21
Power per angle in dBm
Power (dBm)
Angle °

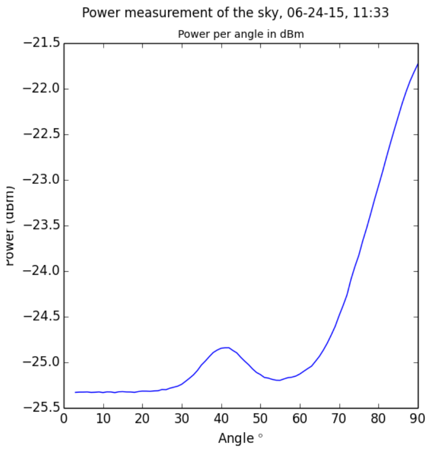

Power measurement of the sky, 06-24-15, 11:22
Power per angle in dBm
Power (dBm)
Angle °

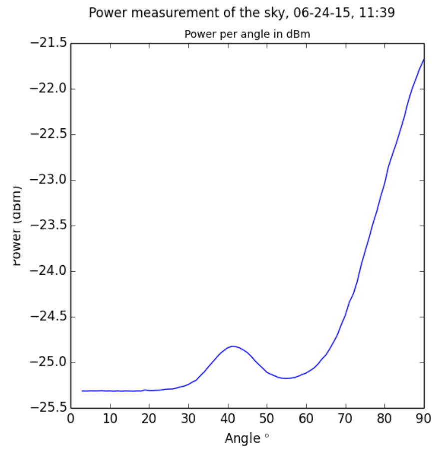

Power measurement of the sky, 06-24-15, 11:24
Power per angle in dBm
Power (dBm)
Angle °

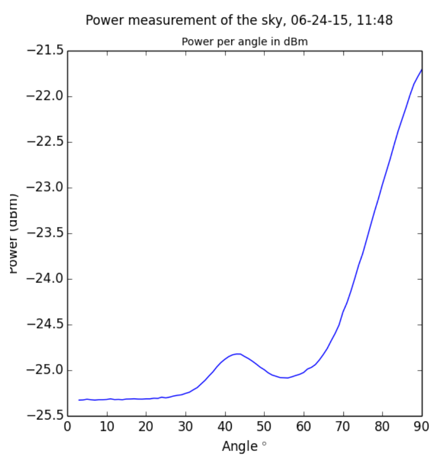

Power measurement of the sky, 06-24-15, 11:25
Power per angle in dBm
Angle °


Power measurement of the sky, 06-24-15, 11:26
Power per angle in dBm
Angle °


Power measurement of the sky, 06-24-15, 11:30
Power per angle in dBm
Angle °


Power measurement of the sky, 06-24-15, 11:33
Power per angle in dBm
Angle °


Power measurement of the sky, 06-24-15, 11:39
Power per angle in dBm
Angle °


Power measurement of the sky, 06-24-15, 11:48
Power per angle in dBm
Angle °

3 Observations 06-30-15

	Time	Observation of..	Measure size (°)	N [5]	T_{atm} (K)	P_{hot} (dBm)	P_{cold} (dBm) [6]	Gain (dB)	Description sky	File name
1	10:16	Sun	1	1	—	-20.94	-23.52	—		data130701.txt
2	10:17	Sun	1	1	—	-20.90	-23.48	—		data131320.txt
3	10:19	Sun	1	1	—	-20.99	-23.56	—		data131558.txt
4	10:21	Sun	1	1	—	-20.98	-23.55	—		data131753.txt
5	10:23	Sun	1	1	—	-20.98	-23.57	—		data131952.txt
6	10:25	CMB	13	1	—	-20.99	-23.22	—		data132217.txt
7	10:16	CMB	13	1	—	-21.01	-23.62	—		data132324.txt
8	10:17	CMB	13	1	—	-21.02	-23.64	—		data132429.txt
9	10:19	CMB	13	1	—	-21.04	-23.66	—		data132533.txt
10	10:21	CMB	13	1	—	-21.06	-23.66	—		data132639.txt
11	10:16	CMB	13	1	—	-21.07	-23.67	—		data132756.txt
12	10:17	CMB	13	1	—	-21.07	-23.67	—		data132905.txt
13	10:19	Sun	1	1	—	-20.91	-23.50	—		data133180.txt
14	10:21	Sun	1	1	—	-20.93	-23.52	—		data134580.txt
15	10:23	Satellite	1	1	—	-21.21	-23.76	—		data141432.txt
16	10:25	Satellite	1	1	—	-21.21	-23.75	—		data141643.txt
17	10:16	Satellite	1	1	—	-21.16	-23.71	—		data142009.txt
18	10:17	Satellite	1	1	—	-21.17	-23.74	—		data145854.txt
19	10:19	Satellite	1	1	—	-21.17	-23.75	—		data150052.txt
20	10:21	Satellite	1	1	—	-21.19	-23.76	—		data150245.txt
21	10:16	Satellite	1	1	—	-21.19	-23.76	—		data150443.txt
22	10:17	Satellite	1	1	—	-21.21	-23.79	—		data150706.txt
23	10:19	Satellite	1	1	—	-21.21	-23.78	—		data150908.txt
24	10:21	Satellite	1	1	—	-21.21	-23.76	—		data151439.txt
25	10:23	Opacity	1	1	—	-21.13	-23.92	—		data151857.txt
26	10:25	Opacity	1	1	—	-21.15	-23.93	—		data152038.txt

[5] Every measurement data point can be a sample of measurements. Integrating over these measurements will decrease the uncertainty of the measurement by $\sqrt{\mathrm{N}}$

[6] The cold load temperature was not measured, only the cold load powers where known.

27	10:16	Opacity	1	1	—	-21.15	-23.94	—		data152221.txt
28	10:17	CMB	13	1	—	-21.15	-23.95	—		data152512.txt
29	10:19	CMB	13	1	—	-21.15	-23.95	—		data152621.txt
30	10:21	CMB	13	1	—	-21.17	-23.96	—		data152726.txt
31	10:16	CMB	13	1	—	-21.17	-23.95	—		data152846.txt
32	10:17	CMB	13	1	—	-21.17	-23.95	—		data152953.txt
33	10:19	CMB	13	1	—	-21.16	-23.94	—		data153104.txt
34	10:21	CMB	13	1	—	-21.16	-23.93	—		data153220.txt
35	10:23	CMB	13	1	—	-21.21	-23.95	—		data153457.txt
36	10:25	CMB	13	1	—	-21.21	-23.95	—		data153602.txt
37	10:16	CMB	13	1	—	-21.22	-23.95	—		data153706.txt
38	10:17	Opacity	1	1	—	-21.24	-23.96	—		data153813.txt
39	10:19	Opacity	1	1	—	-21.24	-23.97	—		data154007.txt
40	10:21	Opacity	1	1	—	-21.25	-23.98	—		data154202.txt

Table 3: Data from observations of the sky on 07-04-15

3.1 Sky observations

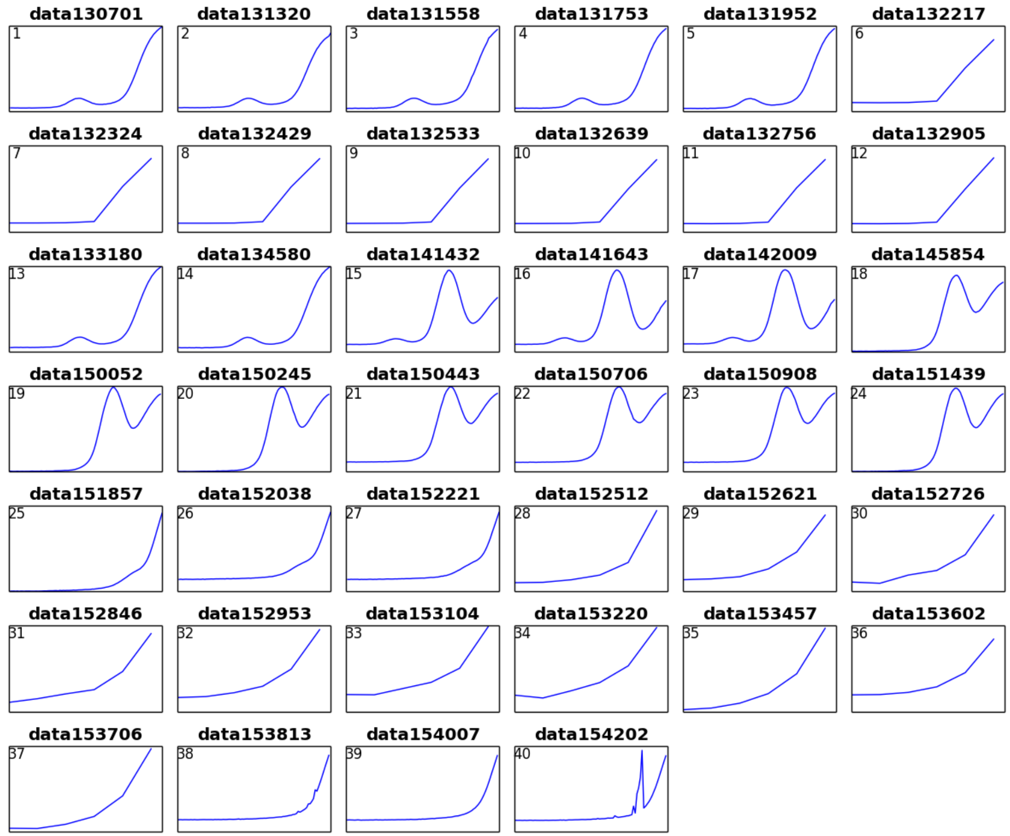
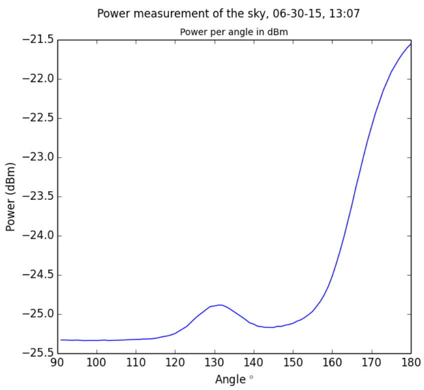
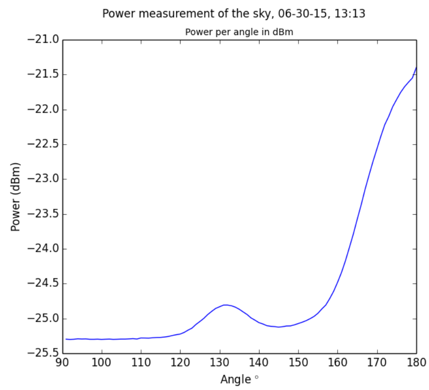
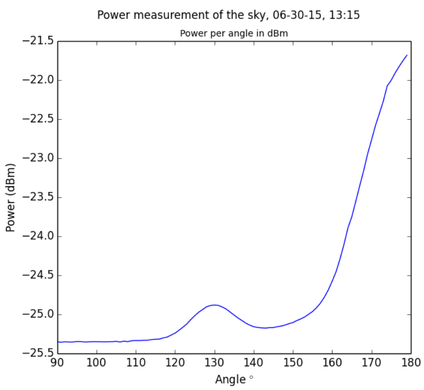
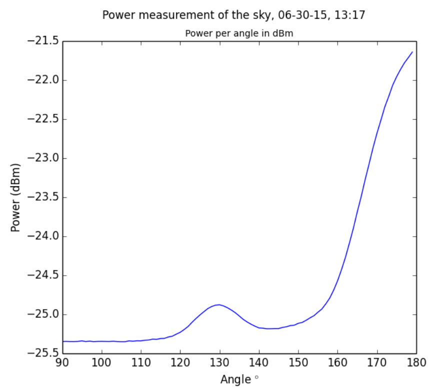


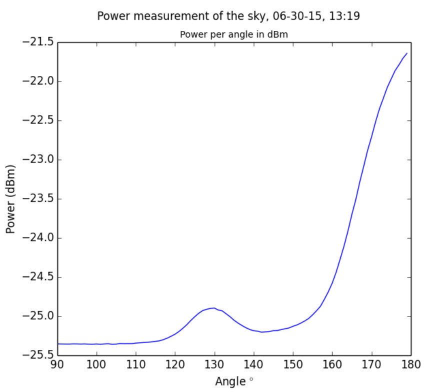
Figure 4: Overview measurements 06-30-2015.

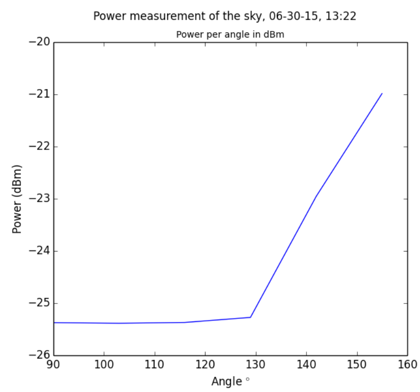

Power measurement of the sky, 06-30-15, 13:07
Power per angle in dBm
Power (dBm)
Angle °

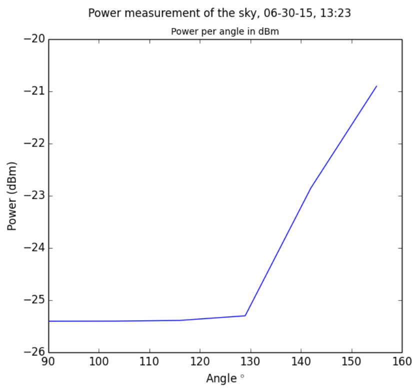

Power measurement of the sky, 06-30-15, 13:13
Power per angle in dBm
Power (dBm)
Angle °

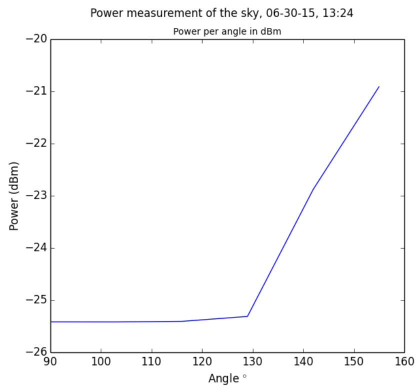

Power measurement of the sky, 06-30-15, 13:15
Power per angle in dBm
Power (dBm)
Angle °

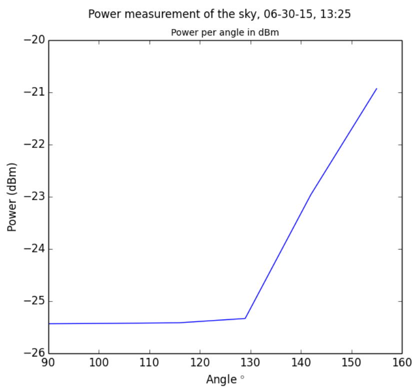

Power measurement of the sky, 06-30-15, 13:17
Power per angle in dBm
Power (dBm)
Angle °

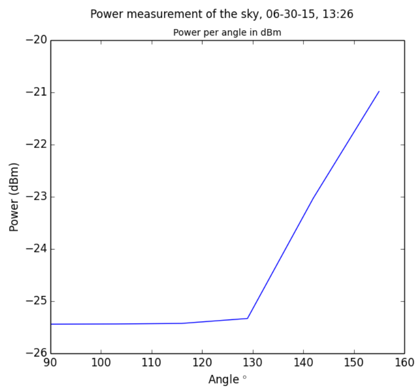

Power measurement of the sky, 06-30-15, 13:19
Power per angle in dBm
Power (dBm)
Angle °

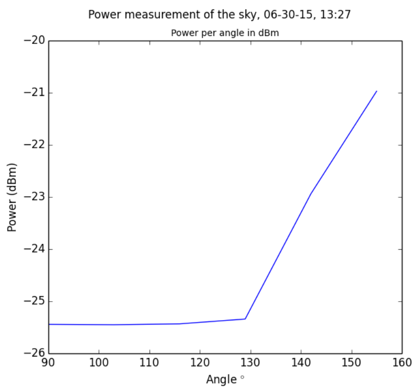

Power measurement of the sky, 06-30-15, 13:22
Power per angle in dBm
Power (dBm)
Angle °

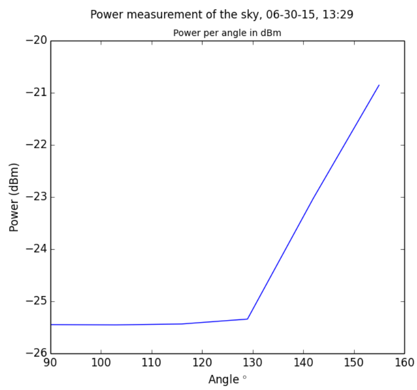

Power measurement of the sky, 06-30-15, 13:23
Power per angle in dBm
Power (dBm)
Angle °

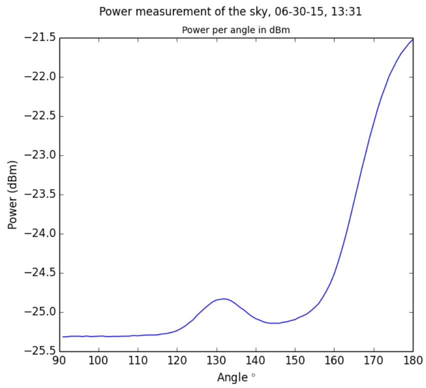

Power measurement of the sky, 06-30-15, 13:24
Power per angle in dBm
Power (dBm)
Angle °

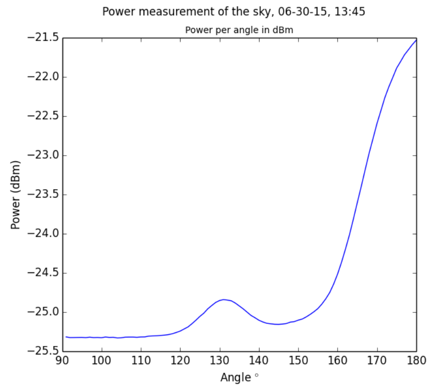

Power measurement of the sky, 06-30-15, 13:25
Power per angle in dBm
Power (dBm)
Angle °

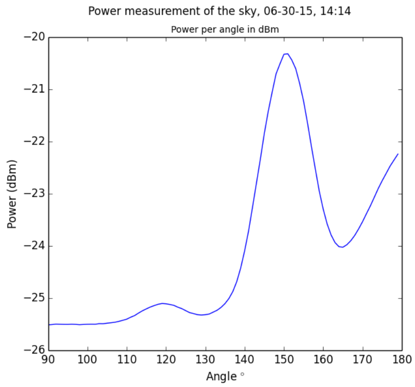

Power measurement of the sky, 06-30-15, 13:26
Power per angle in dBm
Power (dBm)
Angle °

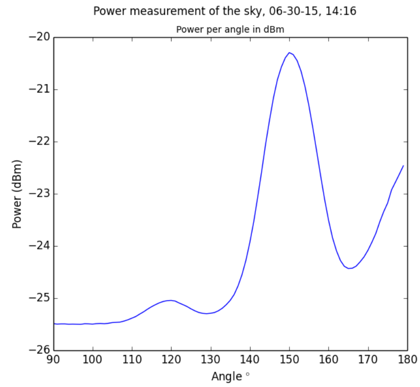

Power measurement of the sky, 06-30-15, 13:27
Power per angle in dBm
Power (dBm)
Angle °

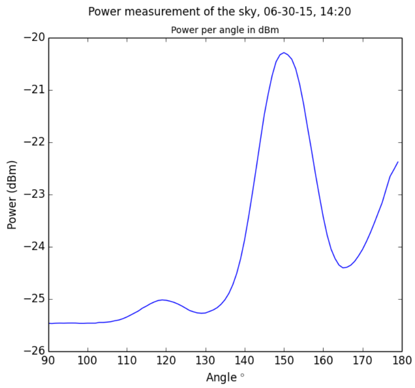

Power measurement of the sky, 06-30-15, 13:29
Power per angle in dBm
Power (dBm)
Angle °

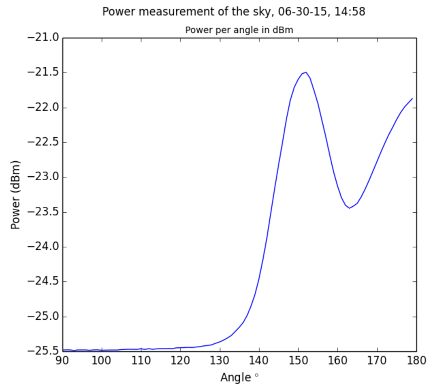

Power measurement of the sky, 06-30-15, 13:31
Power per angle in dBm
Power (dBm)
Angle °

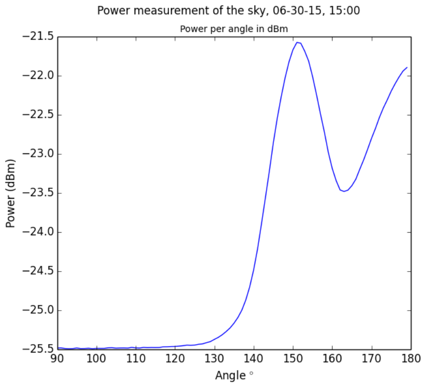

Power measurement of the sky, 06-30-15, 13:45
Power per angle in dBm
Power (dBm)
Angle °

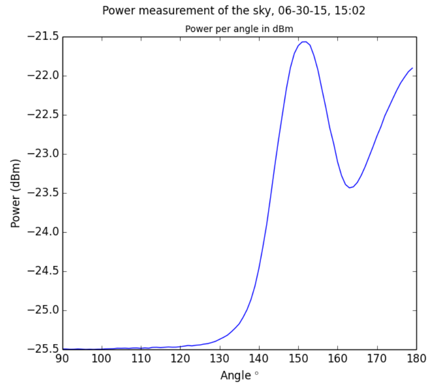

Power measurement of the sky, 06-30-15, 14:14
Power per angle in dBm
Power (dBm)
Angle °

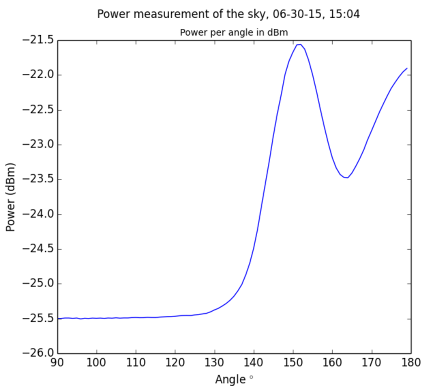

Power measurement of the sky, 06-30-15, 14:16
Power per angle in dBm
Power (dBm)
Angle °

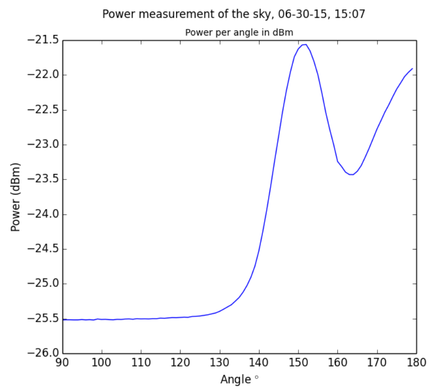

Power measurement of the sky, 06-30-15, 14:20
Power per angle in dBm
Power (dBm)
Angle °

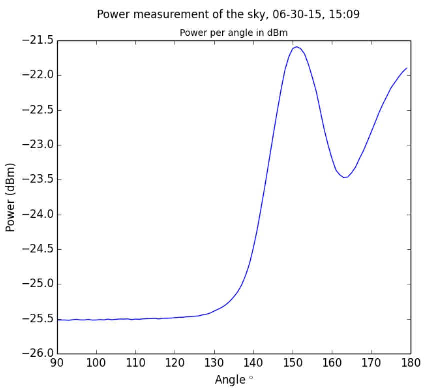

Power measurement of the sky, 06-30-15, 14:58
Power per angle in dBm
Power (dBm)
Angle °

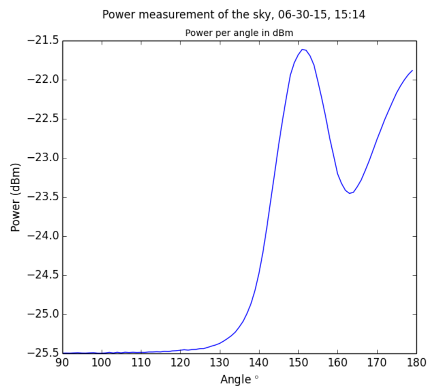

Power measurement of the sky, 06-30-15, 15:00
Power per angle in dBm
Power (dBm)
Angle °

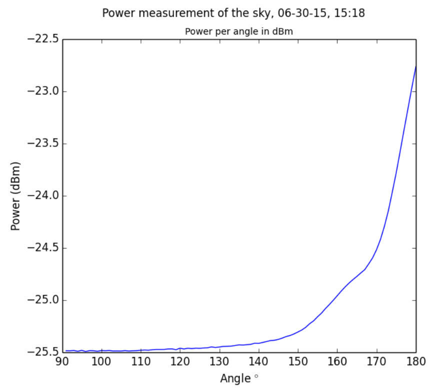

Power measurement of the sky, 06-30-15, 15:02
Power per angle in dBm
Power (dBm)
Angle °

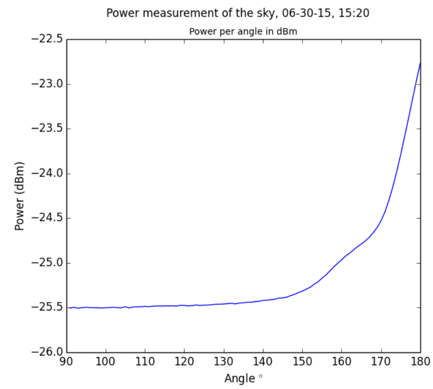

Power measurement of the sky, 06-30-15, 15:04
Power per angle in dBm
Power (dBm)
Angle °

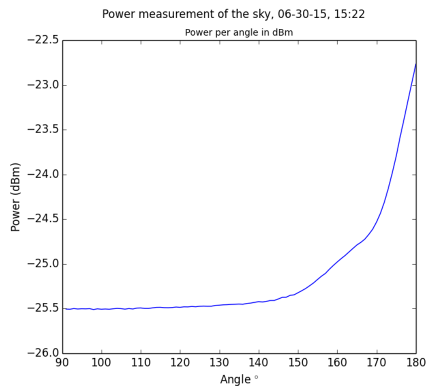

Power measurement of the sky, 06-30-15, 15:07
Power per angle in dBm
Power (dBm)
Angle °

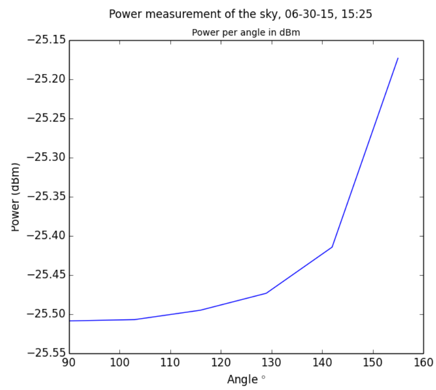

Power measurement of the sky, 06-30-15, 15:09
Power per angle in dBm
Power (dBm)
Angle °

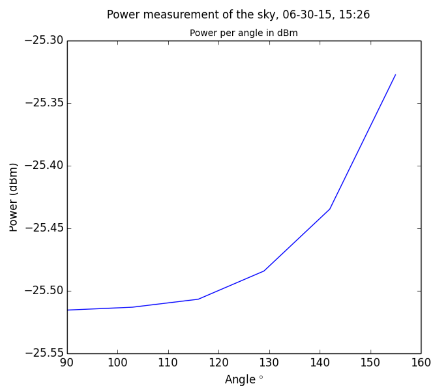

Power measurement of the sky, 06-30-15, 15:14
Power per angle in dBm
Power (dBm)
Angle °

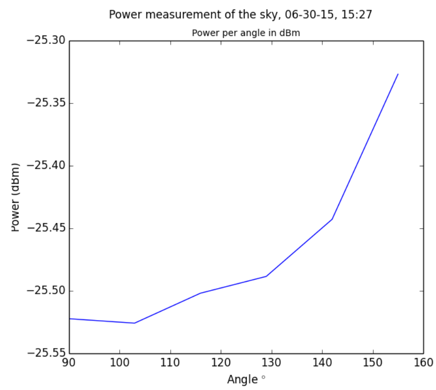

Power measurement of the sky, 06-30-15, 15:18
Power per angle in dBm
Power (dBm)
Angle °

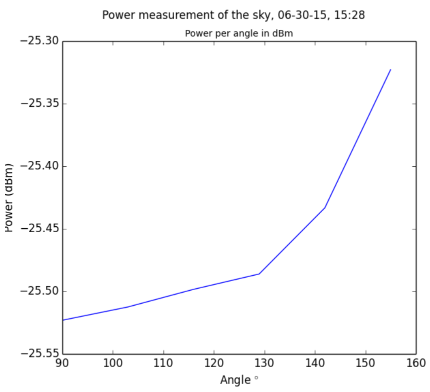

Power measurement of the sky, 06-30-15, 15:20
Power per angle in dBm
Power (dBm)
Angle °

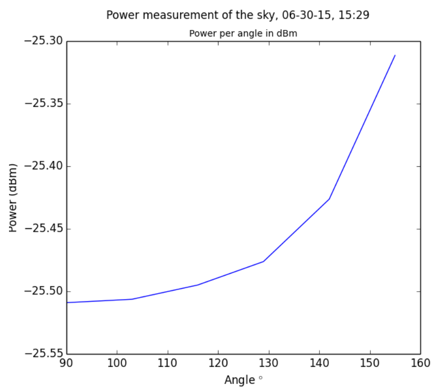

Power measurement of the sky, 06-30-15, 15:22
Power per angle in dBm
Power (dBm)
Angle °

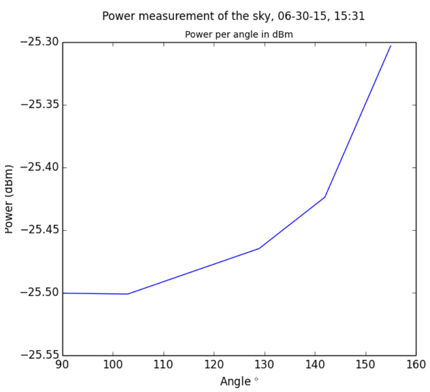

Power measurement of the sky, 06-30-15, 15:25
Power per angle in dBm
Power (dBm)
Angle °

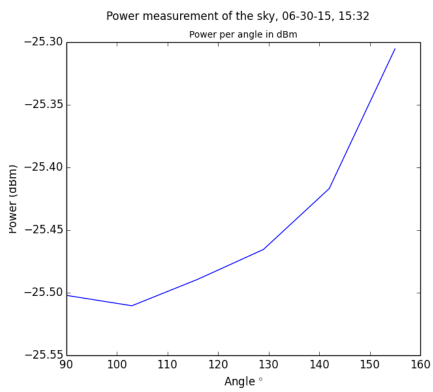

Power measurement of the sky, 06-30-15, 15:26
Power per angle in dBm
Power (dBm)
Angle °

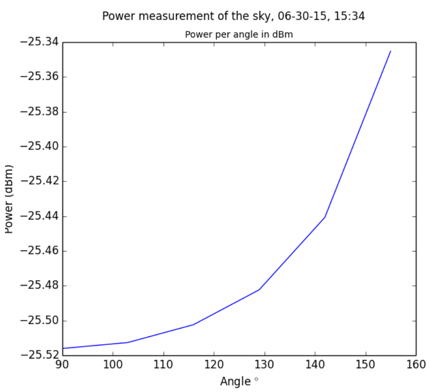

Power measurement of the sky, 06-30-15, 15:27
Power per angle in dBm
Power (dBm)
Angle °

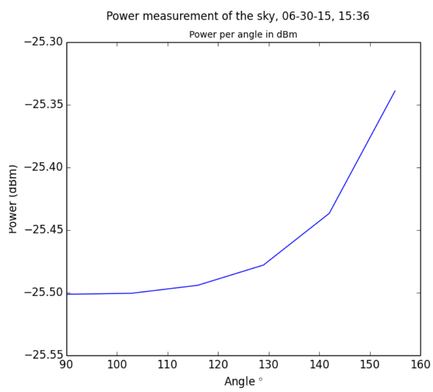

Power measurement of the sky, 06-30-15, 15:28
Power per angle in dBm
Power (dBm)
Angle °

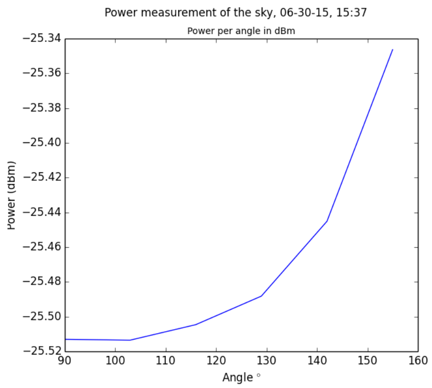

Power measurement of the sky, 06-30-15, 15:29
Power per angle in dBm
Power (dBm)
Angle °

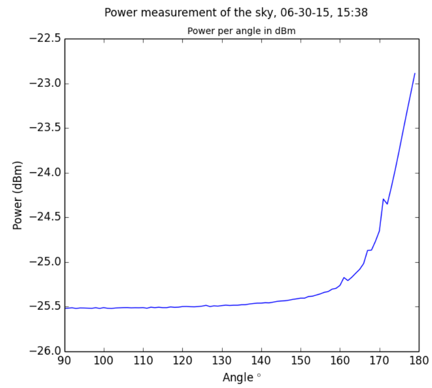

Power measurement of the sky, 06-30-15, 15:31
Power per angle in dBm
Power (dBm)
Angle °

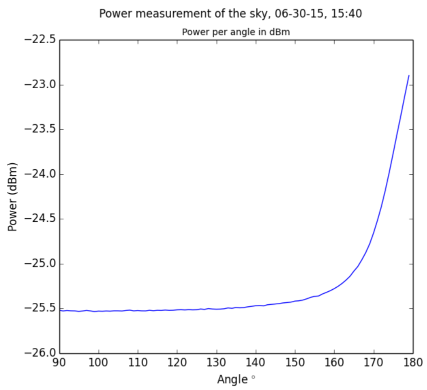

Power measurement of the sky, 06-30-15, 15:32
Power per angle in dBm
Power (dBm)
Angle °

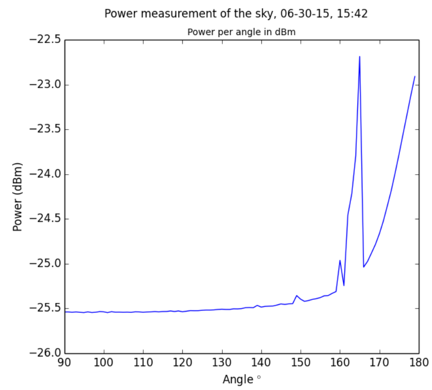

Power measurement of the sky, 06-30-15, 15:34
Power per angle in dBm
Power (dBm)
Angle °


Power measurement of the sky, 06-30-15, 15:36
Power per angle in dBm
Power (dBm)
Angle °


Power measurement of the sky, 06-30-15, 15:37
Power per angle in dBm
Power (dBm)
Angle °


Power measurement of the sky, 06-30-15, 15:38
Power per angle in dBm
Power (dBm)
Angle °


Power measurement of the sky, 06-30-15, 15:40
Power per angle in dBm
Power (dBm)
Angle °


Power measurement of the sky, 06-30-15, 15:42
Power per angle in dBm
Power (dBm)
Angle °

3.2 Hot-Coldload measurements

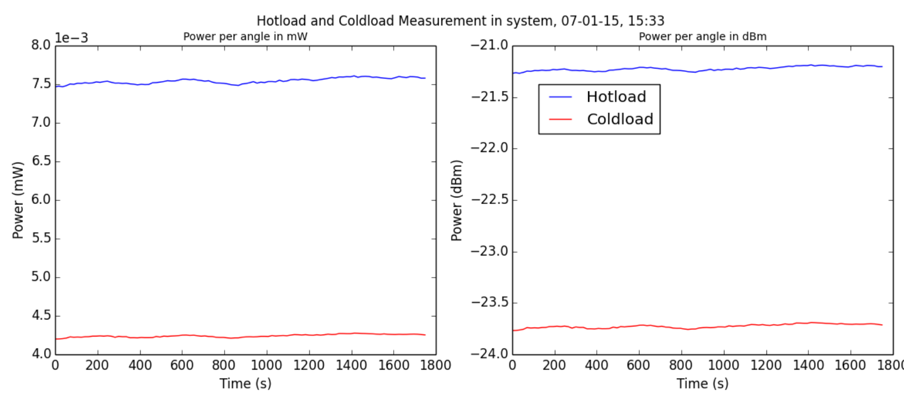
	Time	Amount measurements [7]	N [8]	T_{atm} (K)[9]	T_{hot} (K) [10]	T_{cold} (K) [11]	P_{hot} (dBm)	P_{cold} (dBm)	T_{rec} (K)	Y-factor$_{real}$ [12]	Y-factor$_{sys}$	Gain$_{sys}$ (dB)	Remarks	File name
1	13:09	20	1	298	300	89.28	-20.97	-23.55	170.49	1.8999	1.8112	60.94		data130935.txt
2	14:05	20	1	298	300	79.90	-21.12	-23.71	190.12	1.8338	1.8151	60.41		data140504.txt
3	14:06	20	1	298	300	76.41	-21.21	-23.77	203.02	1.7954	1.8002	60.14		data140627.txt
4	14:11	20	1	298	300	79.40	-21.13	-23.72	190.78	1.8317	1.8165	60.40		data141148.txt
5	14:46	20	1	298	300	81.23	-21.14	-23.69	192.68	1.8259	1.7987	60.40		data144654.txt
5	14:46	20	1	298	300	78.18	-21.18	-23.74	198.28	1.8091	1.8023	60.25		data145215.txt

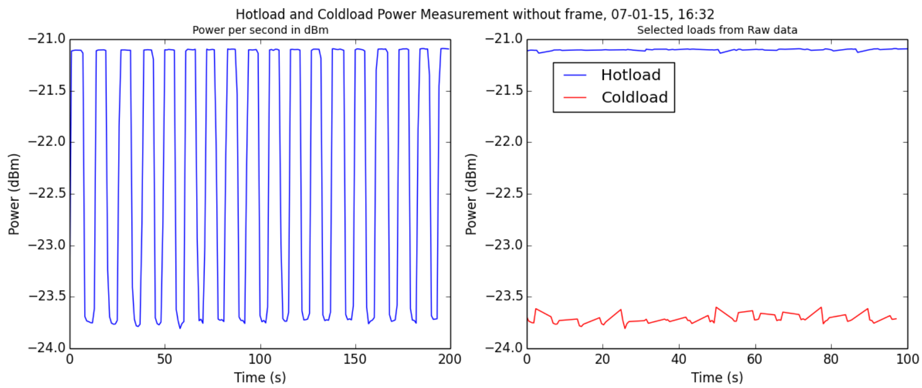
Table 4: Data from calibration measurements on 06-30-15

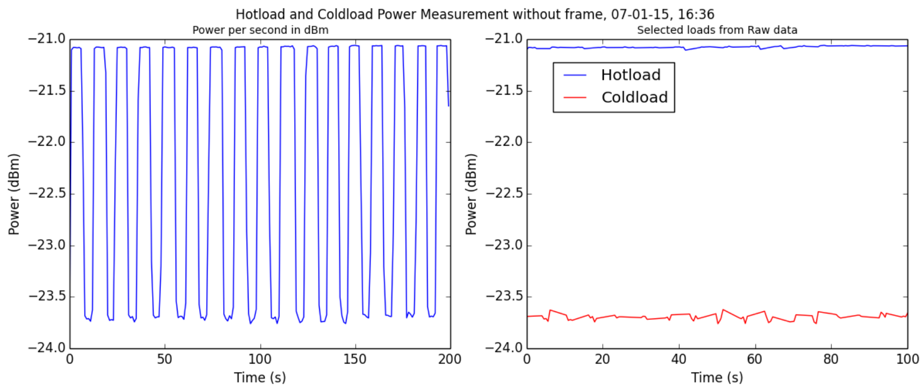
4 Observations 07-01-15

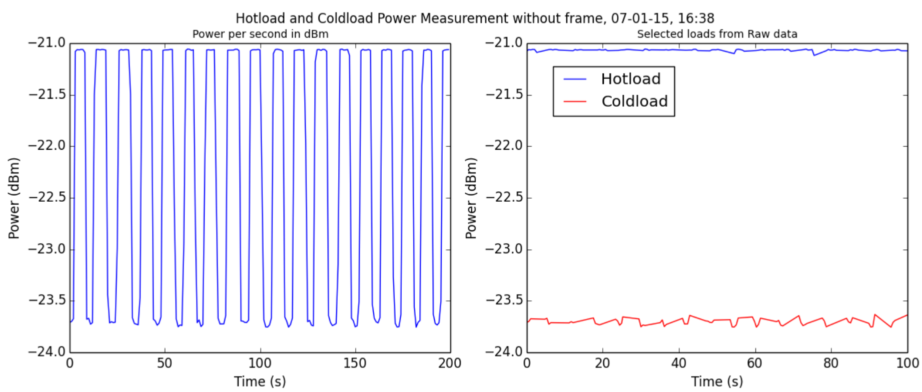
4.1 Hot-Coldload measurements

	Time	Amount measurements [13]	N [14]	T_{atm} (K)[15]	T_{hot} (K) [16]	T_{cold} (K) [17]	P_{hot} (dBm)	P_{cold} (dBm)	T_{rec} (K)	Y-factor$_{real}$ [18]	Y-factor$_{sys}$	Gain$_{sys}$ (dB)	Remarks	File name
1	15:33	100	1	305.8	314.14	79.20	-21.22	-23.73	222.50	1.7987	1.7787	59.90	System measurement	data153303.txt
2	16:32	37	1	305	311	79.51	-21.10	-23.72	200.50	1.8422	1.8266	60.24	Manual measurement	data163217_beampat.txt
3	16:36	140	1	305	311	80.73	-21.07	-23.70	196.70	1.8538	1.8299	60.32	Manual measurement	data163652_beampat.txt
4	16:38	142	1	305	311	80.21	-21.06	-23.71	195.62	1.8572	1.8366	60.33	Manual measurement	data163855_beampat.txt




Hotload and Coldload Power Measurement without frame, 07-01-15, 16:32
Power per second in dBm
Selected loads from Raw data
Power (dBm)
Time (s)
Hotload
Coldload


Hotload and Coldload Power Measurement without frame, 07-01-15, 16:36
Power per second in dBm
Selected loads from Raw data
Power (dBm)
Time (s)
Hotload
Coldload


Hotload and Coldload Power Measurement without frame, 07-01-15, 16:38
Power per second in dBm
Selected loads from Raw data
Power (dBm)
Time (s)
Hotload
Coldload

5 Observations 07-04-15

It is today a very hot day. The temperature reaches values of >30 °C. Because of the heat it is very cloudy. The Sun shines strongly and it is very muggy.




	Time	Observation of..	Measure size (°)	N [19]	T_{atm} (K)	T_{hot} (K)	T_{cold} (K) [20]	Gain (dB)	Description sky	File name
1	10:16	CMB	13	1	301.5	307.1	95.9	60.46	The clouds are equally spread over the whole sky.	data101653.txt
2	10:17	CMB	13	1	301.7	307.5	95.9	60.45		data101758.txt
3	10:19	CMB	13	1	301.4	308.1	95.6	60.43		data101902.txt
4	10:21	Opacity	1	1	300.9	307.7	94.5	60.40		data102124.txt
5	10:23	Opacity	1	1	300.9	306.4	94.6	60.43	There is a little bit of blue sky coming through the clouds.	data102318.txt
6	10:25	Opacity	1	1	301.0	306.4	94.2	60.42		data102513.txt

Table 5: Data from observations of the sky on 07-04-15

5.1 Sky observations

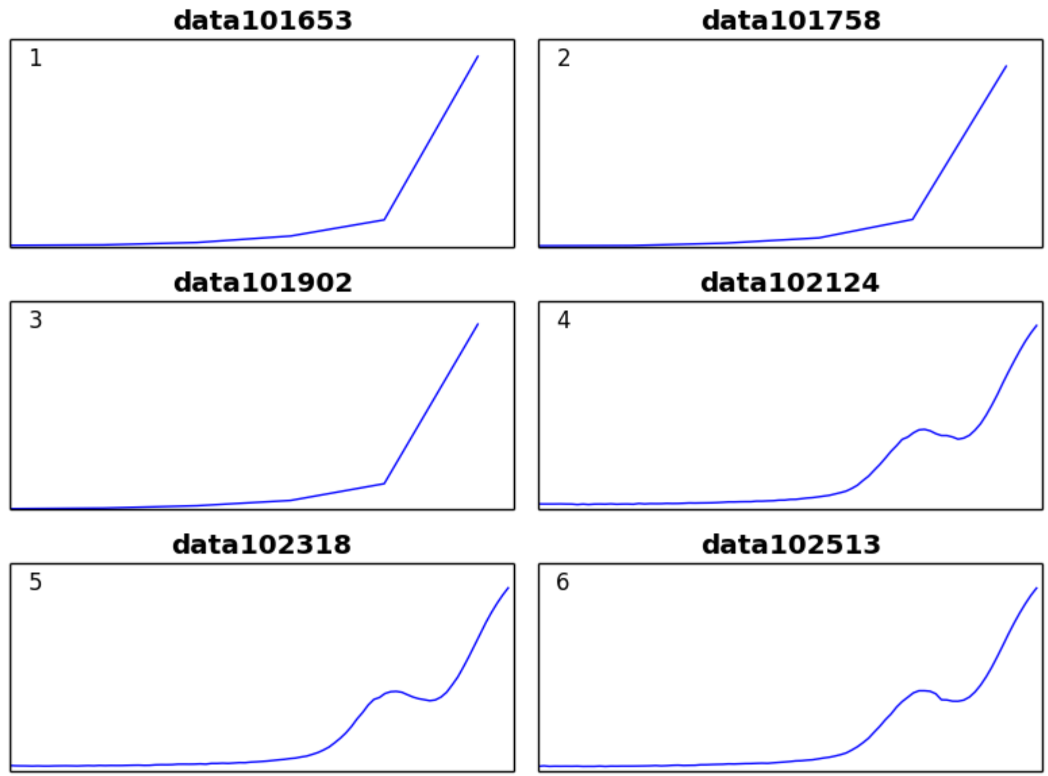
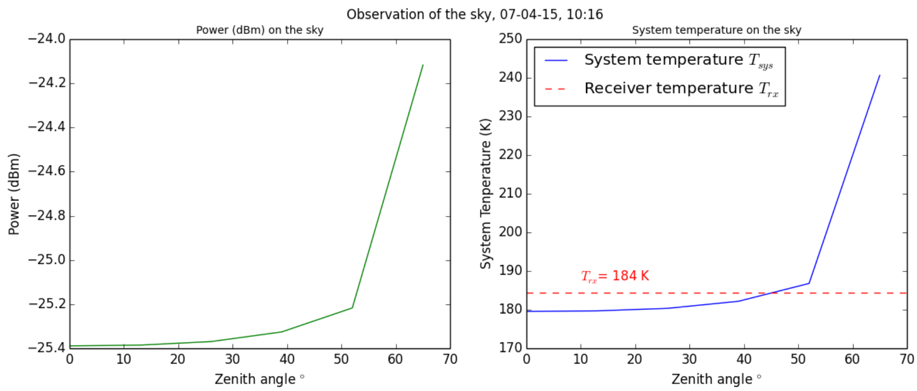
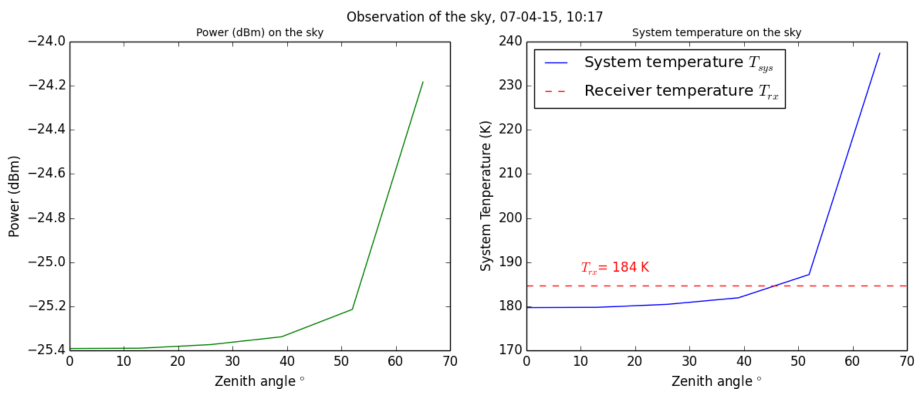
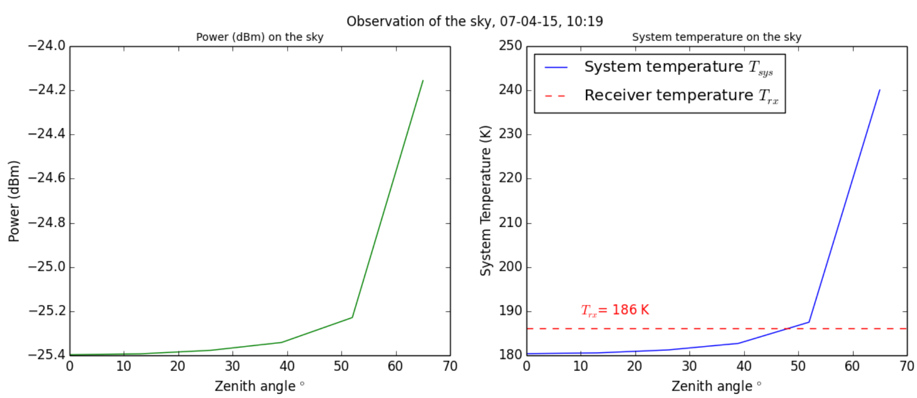
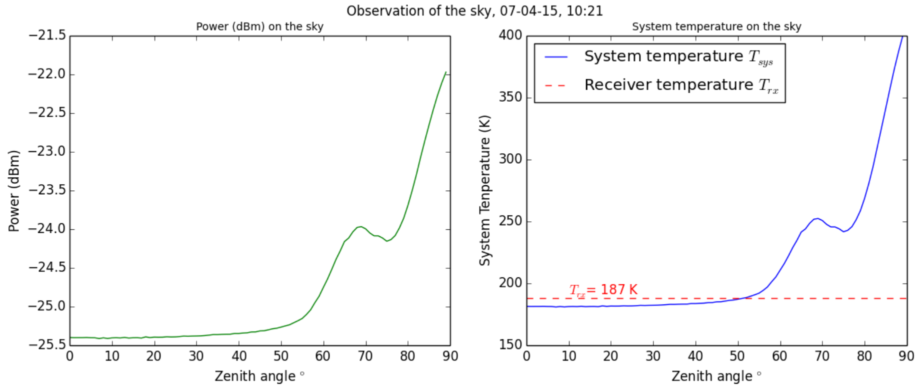


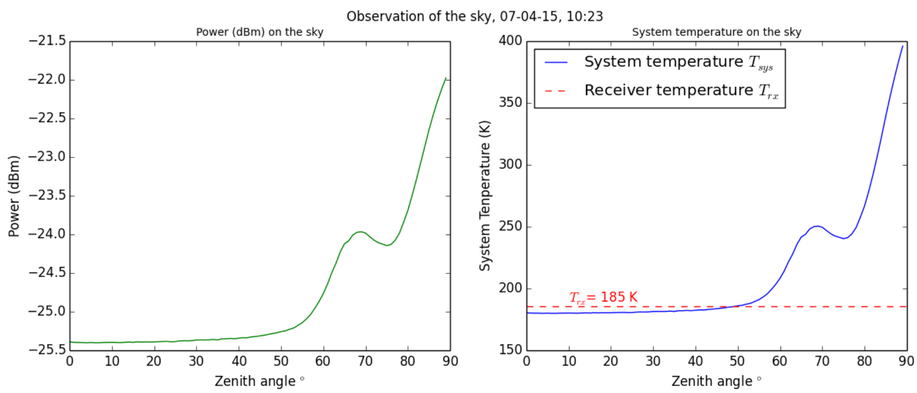
Figure 5: Overview measurements 07-04-2015.

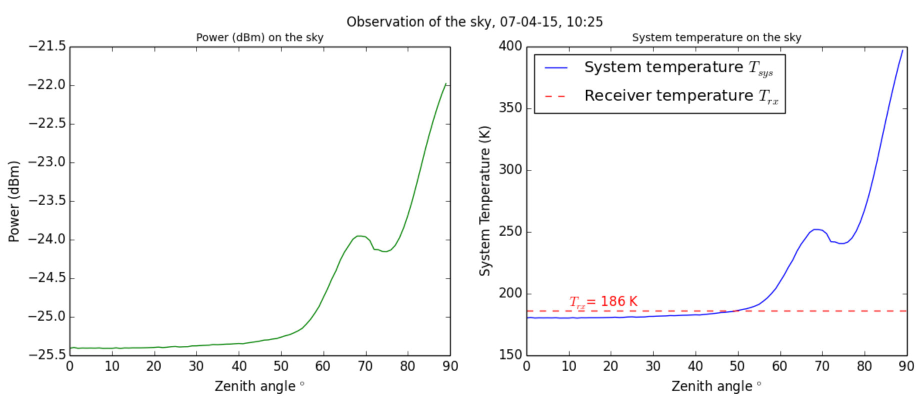

Observation of the sky, 07-04-15, 10:16
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 184 K
System Tenperature (K)
Zenith angle °


Observation of the sky, 07-04-15, 10:17
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 184 K
System Tenperature (K)
Zenith angle °


Observation of the sky, 07-04-15, 10:19
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 186 K
System Tenperature (K)
Zenith angle °


Observation of the sky, 07-04-15, 10:21
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 187 K
System Tenperature (K)
Zenith angle °


Observation of the sky, 07-04-15, 10:23
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 185 K
System Tenperature (K)
Zenith angle °


Observation of the sky, 07-04-15, 10:25
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 186 K
System Tenperature (K)
Zenith angle °

5.2 Hot-Coldload measurements

	Time	Amount measure-ments [21]	N [22]	T_{atm} (K)	T_{hot} (K)	T_{cold} (K) [23]	P_{hot} (dBm)	P_{cold} (dBm)	T_{rec} (K)	Y-factor$_{real}$ [24]	Y-factor$_{sys}$	Gain$_{sys}$ (dB)	Remarks	File name
1	10:09	20	1	301.1	301.50	96.29	-21.00	-23.44	175.98	1.8863	1.7537	60.99		data100948.txt
2	10:27	20	1	301.1	303.29	93.39	-21.05	-23.49	184.48	1.8643	1.7553	60.78	A few cones are sticking and pointing above the surface of the liquid nitrogen.	data102706.txt

Table 6: Data from calibration measurements on 07-04-15

6 Observations 07-05-15

Today, again is a warm day. Although it is sunny, it seems to be that there is a lot of smog. In the morning there was a warning for smog, which can explain the foggy sky. The air feels fuzzy, but at the same time it is mush cooler in comparison with the other previous days.

6.1 Sky observations

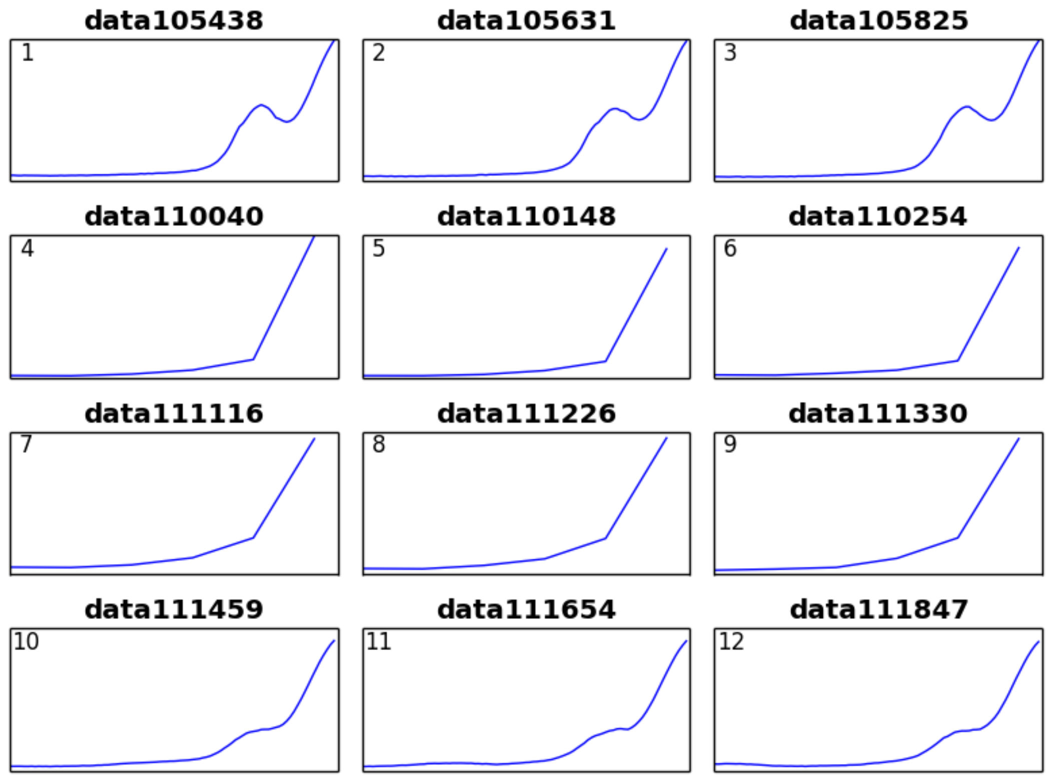
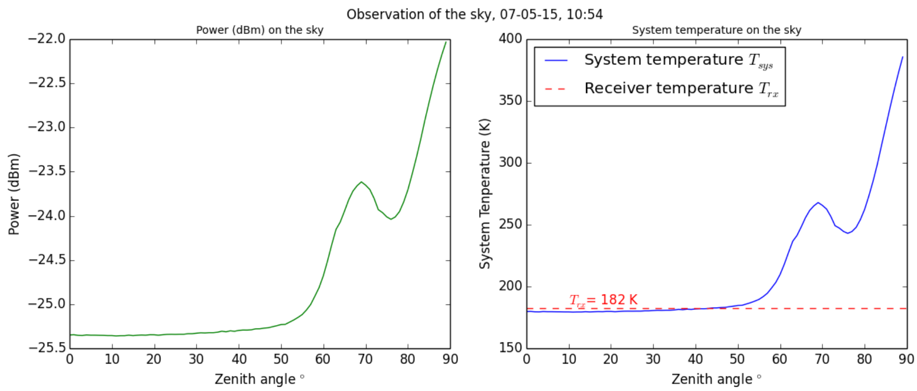
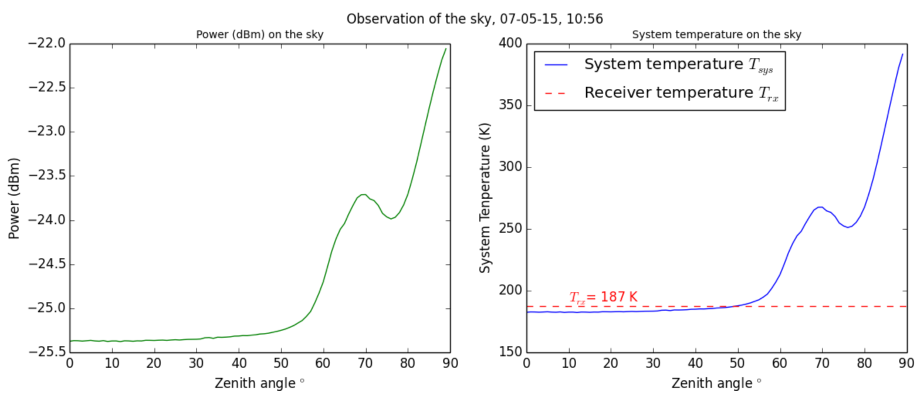


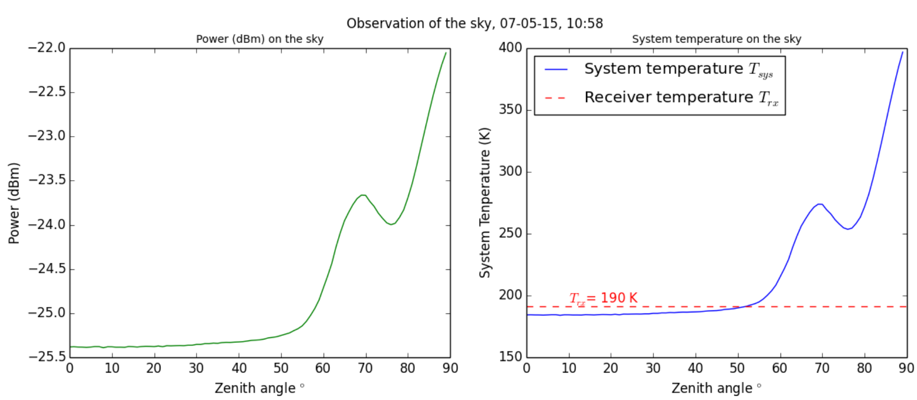
Figure 6: Overview measurements 07-05-2015.

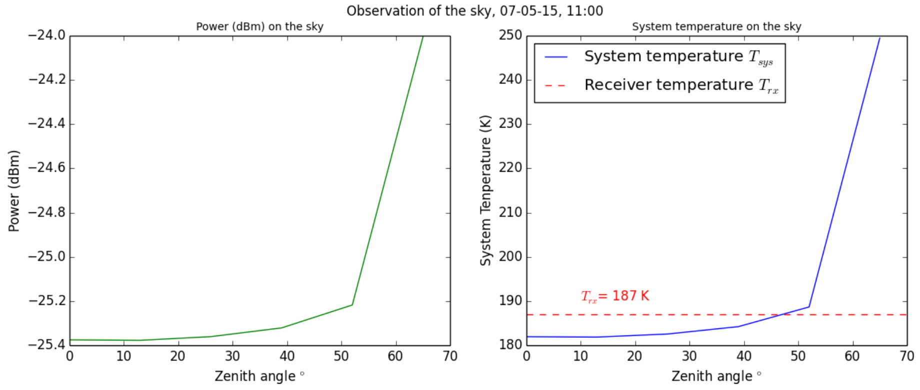
	Time	Observation of..	Measure size (°)	N [25]	T_{atm} (K)	T_{hot} (K)	T_{cold} (K) [26]	Gain (dB)	Description sky	File name
1	10:54	Opacity	1	1	300.6	308.8	96.7	60.49	The Sun is breaking through the clouds, and a chill breeze is blowing.	data105438.txt
2	10:56	Opacity	1	1	299.6	310.9	95.7	60.40		data105631.txt
3	10:58	Opacity	1	1	299.6	311.6	95.1	60.35	During the observation, the Sun is covered with clouds.	data105825.txt
4	11:00	CMB	13	1	299.5	308.6	94.9	60.41		data110040.txt
5	11:01	CMB	13	1	298.5	306.2	95.3	60.47		data110148.txt
6	11:02	CMB	13	1	298.7	305.6	96.1	60.49	The Sun is breaking though the clouds again.	data110254.txt
7	11:11	CMB	13	1	298.2	305.1	97.3	60.56	The Sun is still shining	data111116.txt
8	11:12	CMB	13	1	298.5	306.1	96.1	60.54	The Sun is still shining	data111226.txt
9	11:13	CMB	13	1	398.6	307.3	95.0	60.48	During the observation the Sun is covered with clouds.	data111330.txt
10	11:14	Opacity	1	1	298.7	306.9	95.7	60.47	Sun is breaking through the clouds.	data111459.txt
11	11:16	Opacity	1	1	298.6	306.4	94.8	60.47		data111654.txt
12	11:18	Opacity	1	1	298.5	306.3	94.5	60.46	It is getting really hot.	data111847.txt

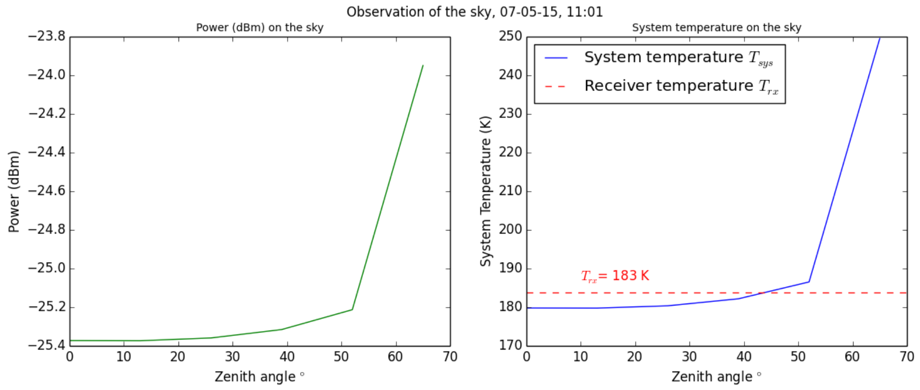
Table 7: Data from observations of the sky on 07-05-15

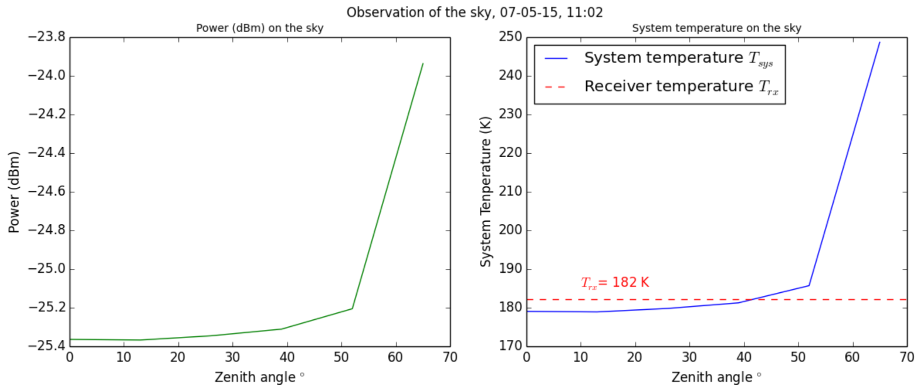

Observation of the sky, 07-05-15, 10:54
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Temperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 182 K
Zenith angle °

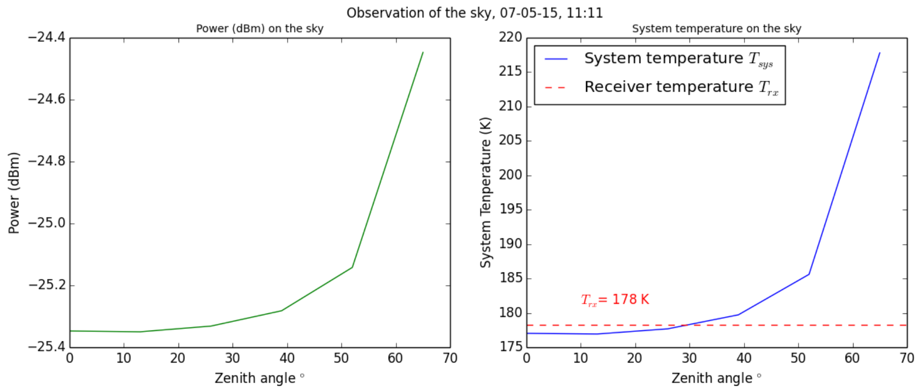

Observation of the sky, 07-05-15, 10:56
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Temperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 187 K
Zenith angle °

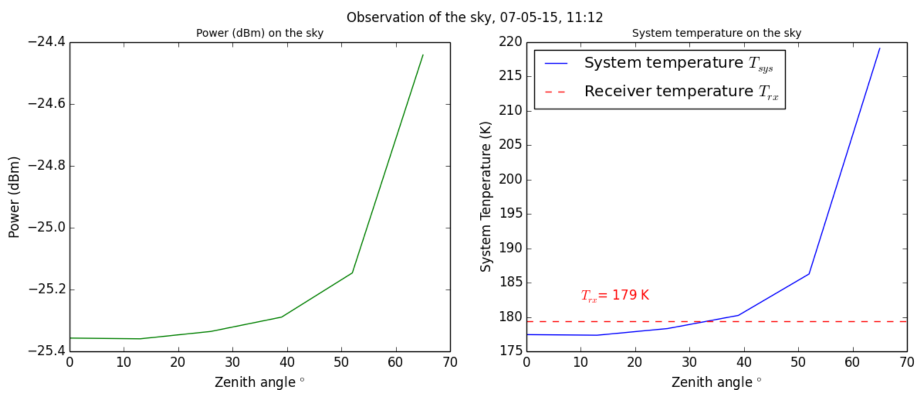

Observation of the sky, 07-05-15, 10:58
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Temperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 190 K
Zenith angle °

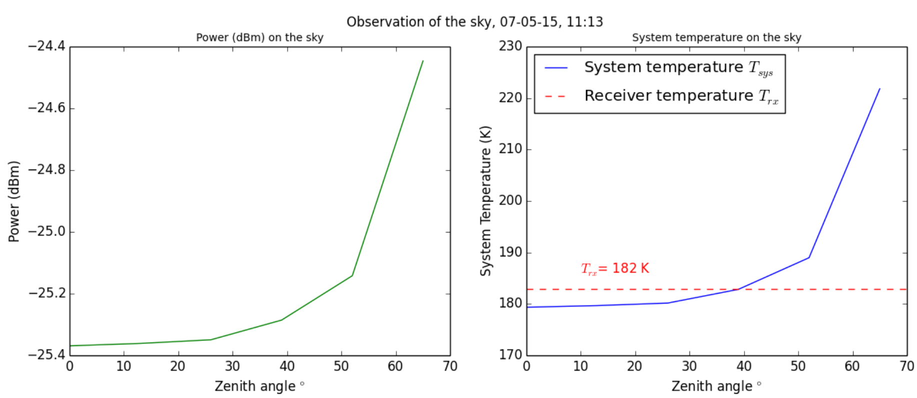

Observation of the sky, 07-05-15, 11:00
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 187 K
Zenith angle °

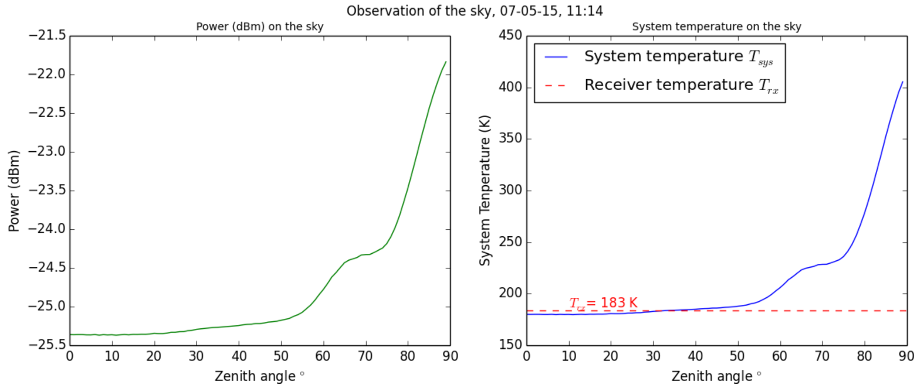

Observation of the sky, 07-05-15, 11:01
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 183 K
Zenith angle °

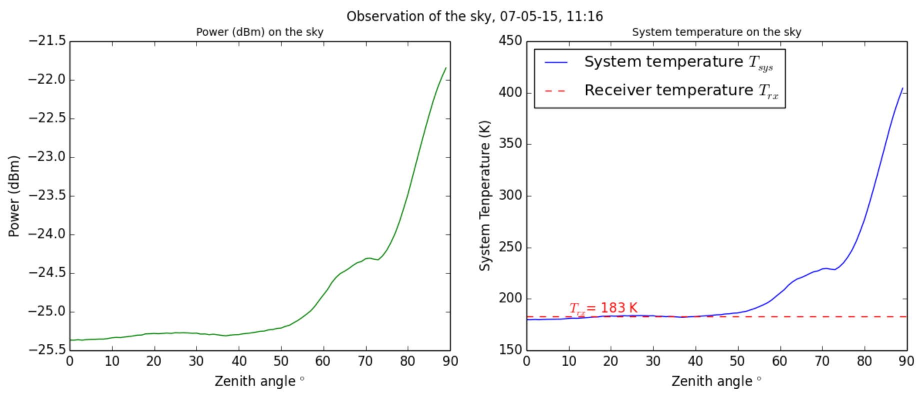

Observation of the sky, 07-05-15, 11:02
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 182 K
Zenith angle °

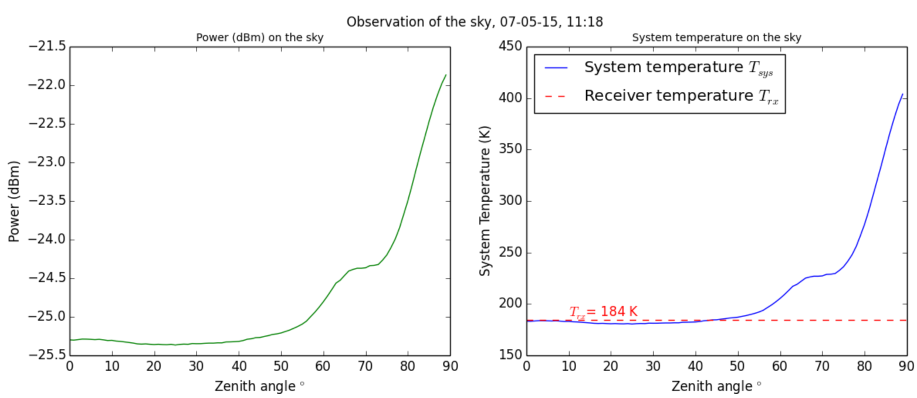

Observation of the sky, 07-05-15, 11:11
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 178 K
Zenith angle °


Observation of the sky, 07-05-15, 11:12
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 179 K
Zenith angle °


Observation of the sky, 07-05-15, 11:13
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 182 K
Zenith angle °


Observation of the sky, 07-05-15, 11:14
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 183 K
System Tenperature (K)
Zenith angle °


Observation of the sky, 07-05-15, 11:16
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 183 K
System Tenperature (K)
Zenith angle °


Observation of the sky, 07-05-15, 11:18
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 184 K
System Tenperature (K)
Zenith angle °

6.2 Hot-Coldload measurements

	Time	Amount measurements [27]	N [28]	T_{atm} (K)	T_{hot} (K)	T_{cold} (K) [29]	P_{hot} (dBm)	P_{cold} (dBm)	T_{rec} (K)	Y-factor$_{real}$ [30]	Y-factor$_{sys}$	Gain$_{sys}$ (dB)	Remarks	File name
1	10:47	20	1	299.1	300.14	97.62	-20.95	-23.41	169.02	1.9058	1.7595	61.14		data104746.txt
2	11:04	20	1	298.1	299.21	95.54	-21.00	-23.45	173.80	1.8849	1.7562	61.01		data110406.txt

Table 8: Data from calibration measurements on 07-05-15

7 Observations 07-06-15

Today the sky is covered with opaque clouds, but we can still see some blue dots from the sky. Today it is a lot colder than it was yesterday. Every now and then there is a little freeze breeze. The Sun is covered with clouds, but it is still very light.

7.1 Sky observations

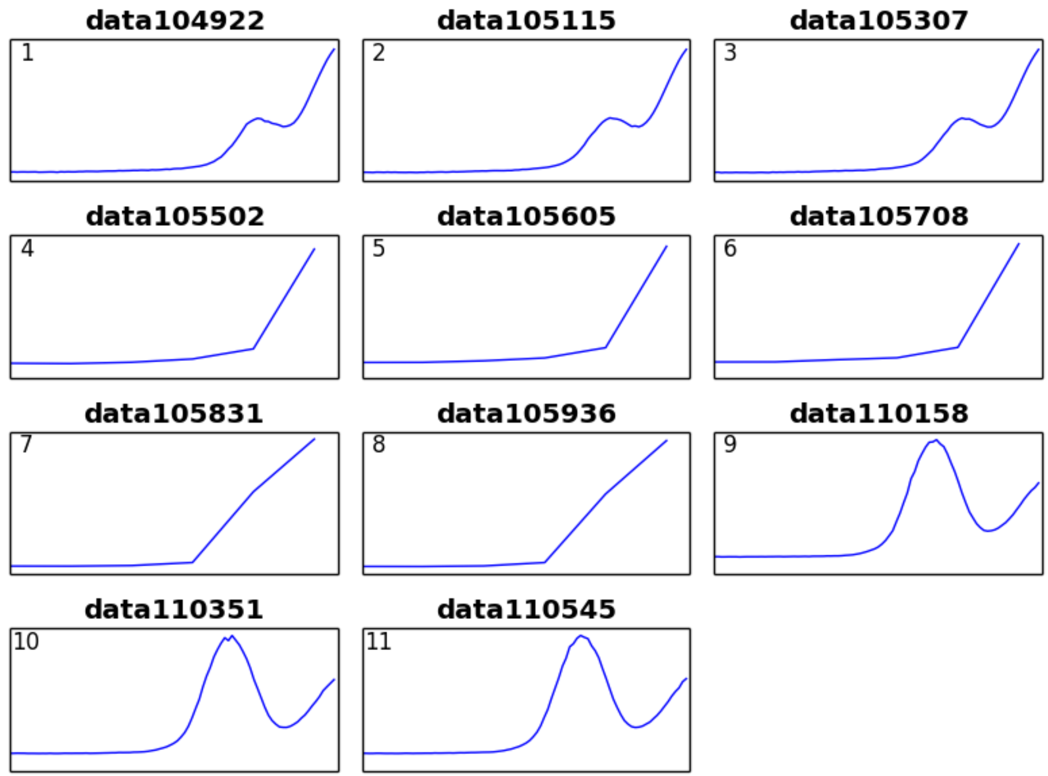
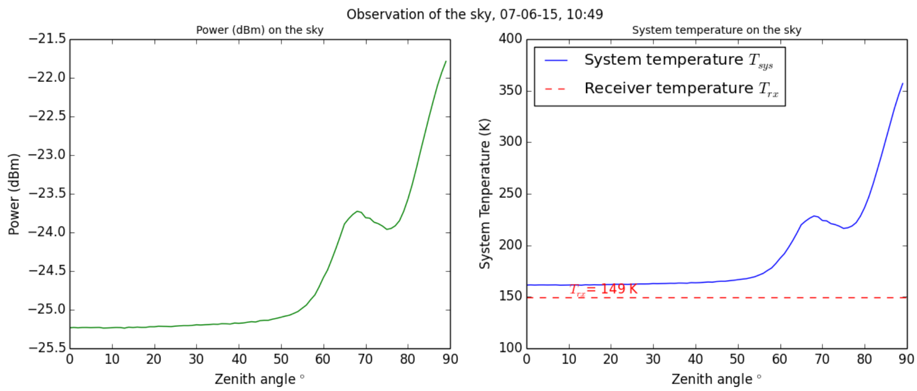
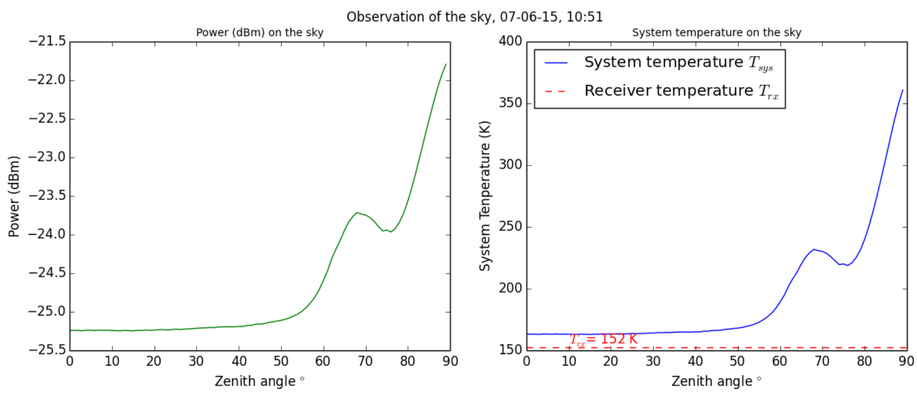


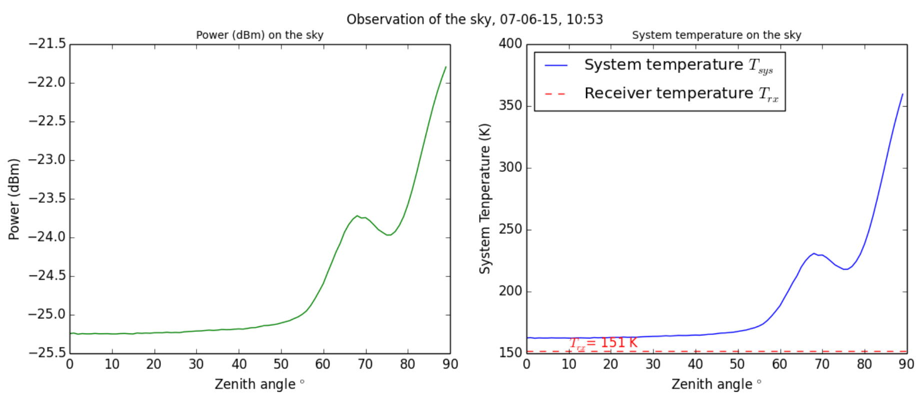
Figure 7: Overview measurements 07-06-2015.

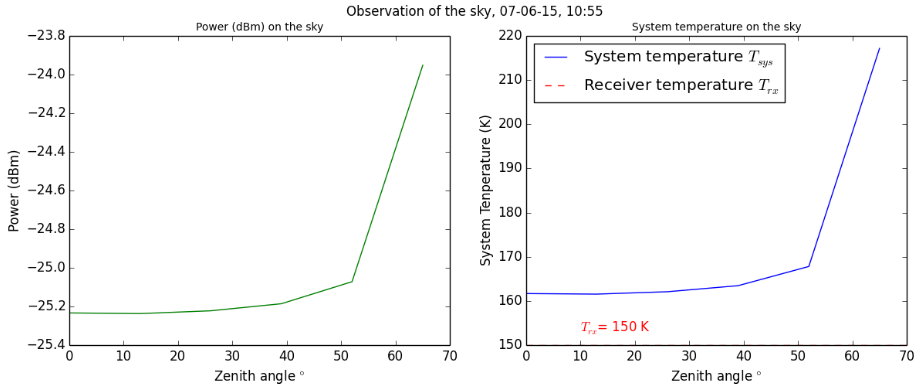
	Time	Observation of..	Measure size (°)	N [31]	T_{atm} (K)	T_{hot} (K)	T_{cold} (K) [32]	Gain (dB)	Description sky	File name
1	10:49	Opacity	1	1	297.3	298.0	102.4	61.07	The Sun is breaking to the ground.	data104922.txt
2	10:51	Opacity	1	1	295.8	298.8	102.2	61.02	The entire sky is filled width yjr blur dots.	data105115.txt
3	10:53	Opacity	1	1	295.9	298.2	102.3	61.03		data105307.txt
4	10:55	CMB	13	1	295.3	297.0	102.0	61.07	The CMB measurements are going so fast that it is hard to describe the sky. During all observations clouds are very random spread.	data105502.txt
5	10:56	CMB	13	1	295.0	296.1	102.7	61.12		data105605.txt
6	10:57	CMB	13	1	295.1	296.1	102.8	61.15	Sun is coming though the clouds during the observation.	data105708.txt
7	10:58	CMB	13	1	295.4	296.8	102.9	61.14		data105831.txt
8	10:56	CMB	13	1	295.7	297.1	102.3	61.12		data105936.txt
9	11:01	Opacity	1	1	295.7	297.3	101.5	61.06		data110158.txt
10	11:03	Opacity	1	1	295.4	297.0	101.6	61.07	The Sun is fully covered by clouds during the observation	data110351.txt
11	11:05	Opacity	1	1	295.3	296.6	101.5	61.09		data110545.txt

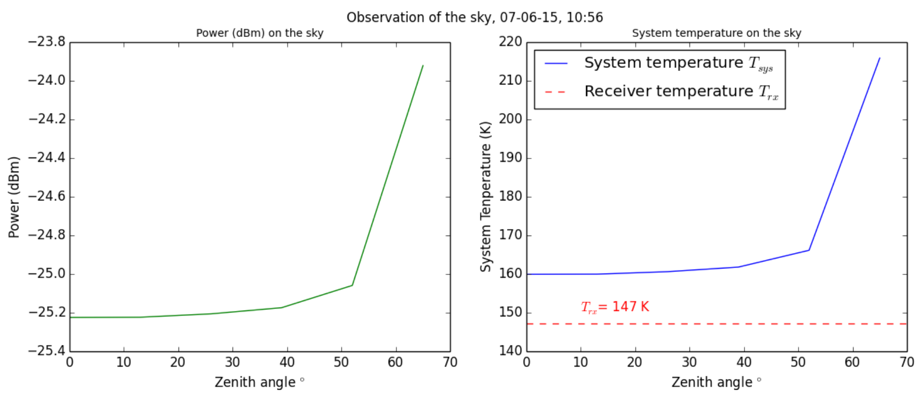
Table 9: Data from observations of the sky on 07-06-15

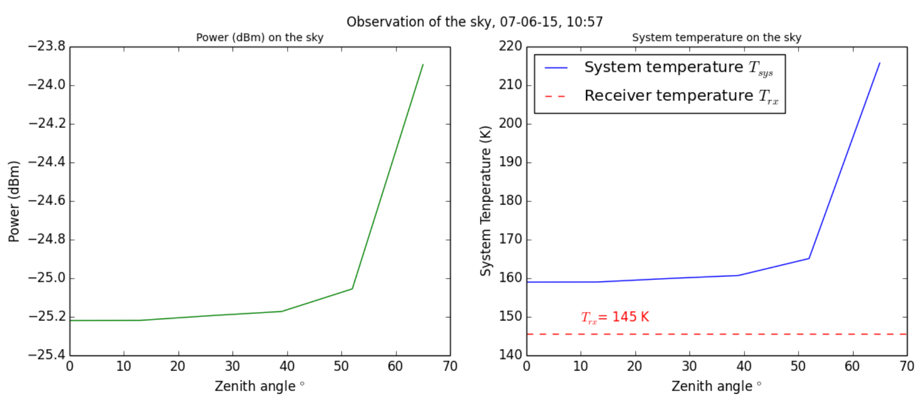

Observation of the sky, 07-06-15, 10:49
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
System Temperature (K)
= 149 K
Zenith angle °

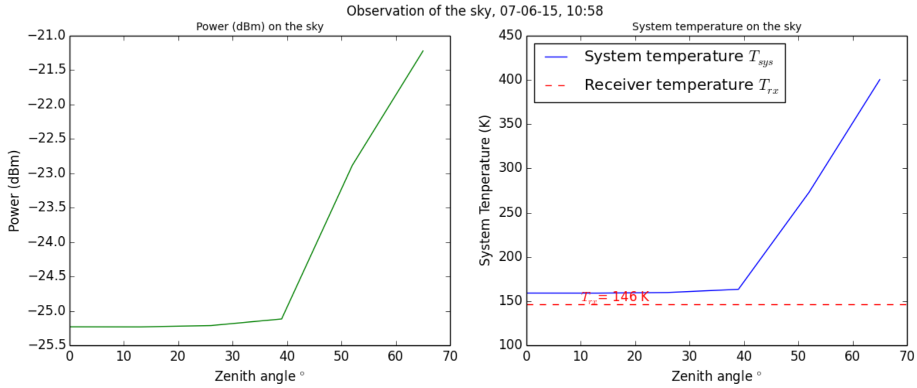

Observation of the sky, 07-06-15, 10:51
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
System Temperature (K)
= 152 K
Zenith angle °

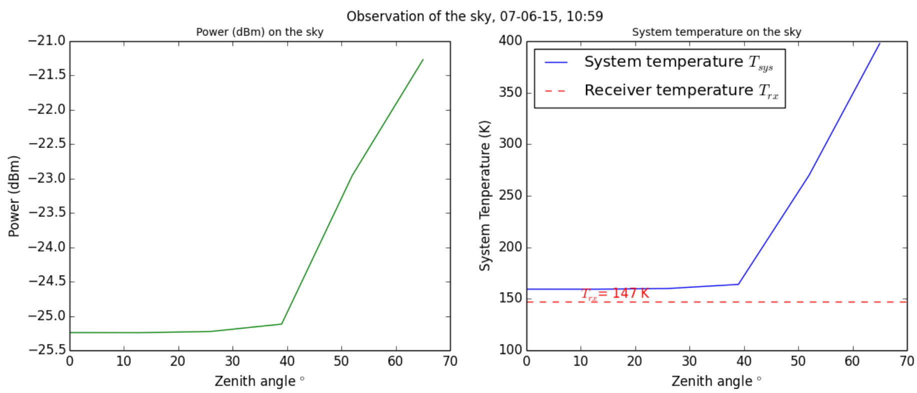

Observation of the sky, 07-06-15, 10:53
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
System Temperature (K)
= 151 K
Zenith angle °

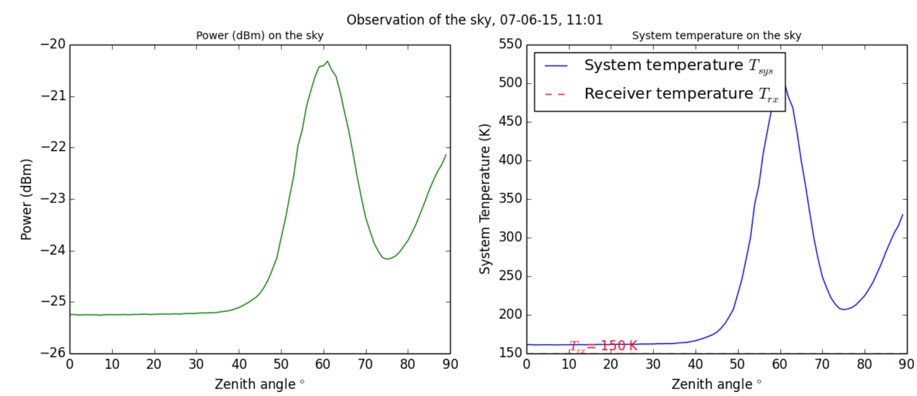

Observation of the sky, 07-06-15, 10:55
Power (dBm) on the sky
System temperature on the sky
Power (dBm)
Zenith angle °
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 150 K
Zenith angle °

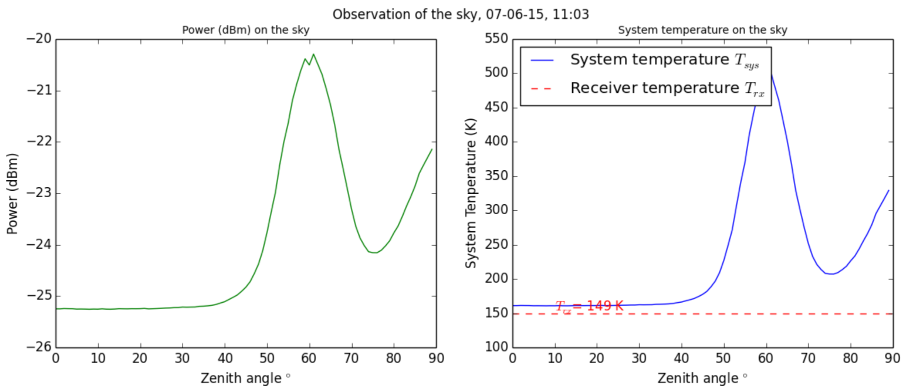

Observation of the sky, 07-06-15, 10:56
Power (dBm) on the sky
System temperature on the sky
Power (dBm)
Zenith angle °
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 147 K
Zenith angle °

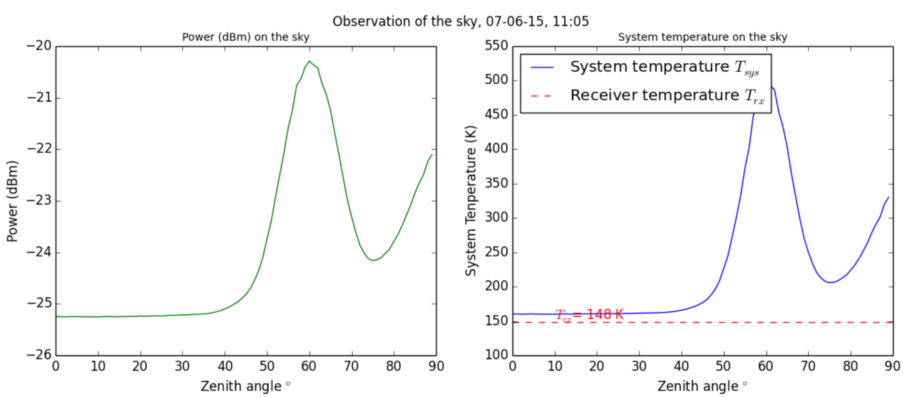

Observation of the sky, 07-06-15, 10:57
Power (dBm) on the sky
System temperature on the sky
Power (dBm)
Zenith angle °
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 145 K
Zenith angle °


Observation of the sky, 07-06-15, 10:58
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 146 K
System Tenperature (K)
Zenith angle °


Observation of the sky, 07-06-15, 10:59
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 147 K
System Tenperature (K)
Zenith angle °


Observation of the sky, 07-06-15, 11:01
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 150 K
System Tenperature (K)
Zenith angle °

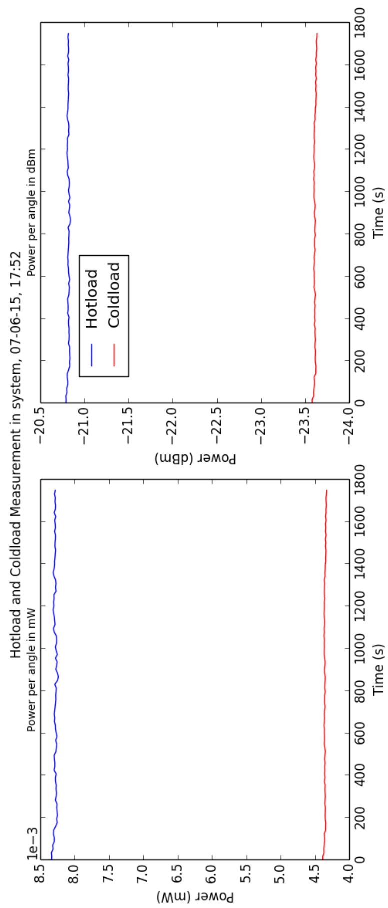

Observation of the sky, 07-06-15, 11:03
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 149 K
Zenith angle °

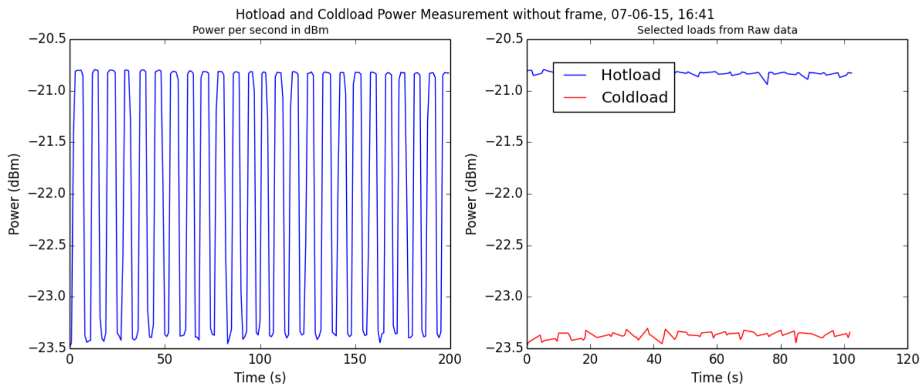

Observation of the sky, 07-06-15, 11:05
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 148 K
Zenith angle °

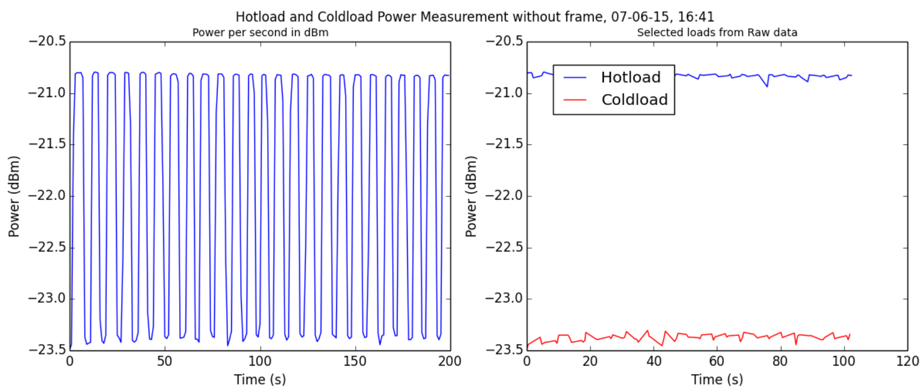
7.2 Hot-Coldload measurements

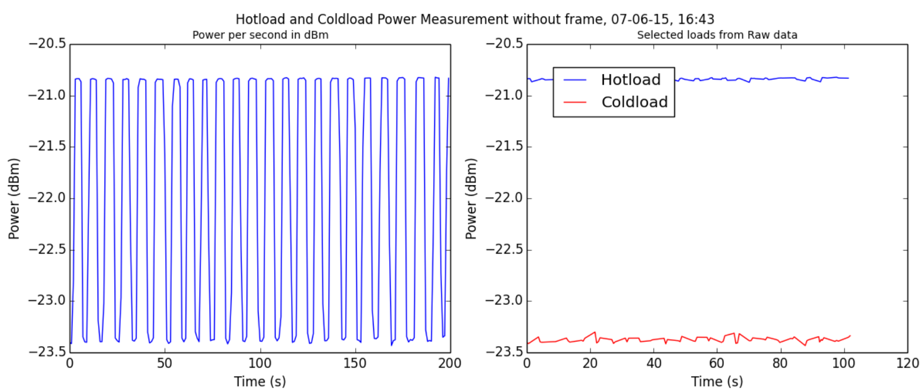
	Time	Amount measurements [33]	N [34]	T_{atm} (K)	T_{hot} (K)	T_{cold} (K) [35]	P_{hot} (dBm)	P_{cold} (dBm)	T_{rec} (K)	Y-factor$_{real}$ [36]	Y-factor$_{sys}$	Gain$_{sys}$ (dB)	Remarks	File name
1	10:47	20	1	297.2	295.27	102.61	-20.80	-23.29	146.11	1.9770	1.7746	61.68	System measurement; Cold load was not put straight into the frame.	data104213.txt
2	11:04	20	1	294.3	294.79	102.68	-20.78	-23.28	144.53	1.9818	1.7771	61.72	System measurement	data110741.txt
3	11:04	140	1	294.3	294.79	98.11	-20.83	-23.38	153.17	1.9631	1.7993	61.43	Manual measurement	data164145_manual.txt
4	11:04	137	1	294.3	294.79	98.27	-20.84	-23.38	154.98	1.9556	1.7925	61.41	Manual measurement	data164349_manual.txt
5	11:04	138	1	294.3	294.79	99.03	-20.84	-23.36	154.79	1.9564	1.7877	61.43	Manual measurement	data164540_manual.txt
6	17:06	20	1	296.6	298.97	82.98	-20.88	-23.65	159.37	1.9379	1.8912	61.01	System measurement	data170632.txt
7	17:52	100	1	297.3	297.39	84.83	-20.82	-23.61	150.65	1.9668	1.9027	61.21	System measurement	data175249.txt

Table 10: Data from calibration measurements on 07-06-15


Hotload and Coldload Measurement in system, 07-06-15, 17:52
Power per angle in mW
Power per angle in dBm
Hotload
Coldload
Power (mW)
Power (dBm)
Time (s)
Time (s)
1e−3


Hotload and Coldload Power Measurement without frame, 07-06-15, 16:41
Power per second in dBm
Selected loads from Raw data
Power (dBm)
Time (s)
Hotload
Coldload


Hotload and Coldload Power Measurement without frame, 07-06-15, 16:41
Power per second in dBm
Selected loads from Raw data
Power (dBm)
Time (s)
Hotload
Coldload


Hotload and Coldload Power Measurement without frame, 07-06-15, 16:43
Power per second in dBm
Selected loads from Raw data
Power (dBm)
Time (s)
Hotload
Coldload

8 Observations 07-07-15

Today is a good day for cloudy observations. There is a cool breeze. The whole sky is white, which means that the clouds should be equally spread over the sky. At some places on the sky the blue air is coming through the white dots.




	Time	Observation of..	Measure size (°)	N [37]	T_{atm} (K)	T_{hot} (K)	T_{cold} (K) [38]	Gain (dB)	Description sky	File name

[37] Every measurement data point can be a sample of measurements. Integrating over these measurements will decrease the uncertainty of the measurement by $\sqrt{\mathrm{N}}$

[38] The cold load is measured after the observation because of the fact that the cold load was too small to fill the entire beam of the antenna.

1	12:24	Opacity	1	1	302.2	300.7	100.0	60.79	Near the horizon there is a think white cloud covering	data122416_tau.txt
2	12:25	Opacity	1	1	302.9	300.6	99.8	60.80		data122558_tau.txt
3	12:27	Opacity	1	1	301.5	300.3	99.5	60.79	Around the angles of 70° till 85° the sky is visible between all the clouds.	data122739_tau.txt
4	12:29	CMB	13	1	301.5	300.2	99.3	60.79		data122924_cmb.txt
5	12:30	CMB	13	1	301.2	300.1	99.3	60.80		data123018_cmb.txt
6	12:31	CMB	13	1	301.0	300.0	99.3	60.81	The clouds seems to be litte white dots. I think that de desciption 'cotton balls' fits the view. The clouds are not equally spread over the sky, but in the horizontal direction they are. This is good because we have our larger side-lobes in this direction.	data123110_cmb.txt
7	12:32	Opacity	1	1	300.3	300.3	99.6	60.79	The telescope is turned towards the Duisenberg building. I try not to hit the building, but this is difficult because our large range of the beam size.	data123257_tau.txt

8	12:34	Opacity	1	1	300.9	300.0	99.8	60.81	The sky is fully white during this observation.	data123437_tau.txt
9	12:36	Opacity	1	1	300.8	299.9	99.5	60.81		data123617_tau.txt
10	12:37	CMB	13	1	300.9	299.8	100.0	60.81	During the observation there is no little piece of sky coming thought the clouds.	data123759_cmb.txt
11	12:38	CMB	13	1	301.9	299.9	100.0	60.81	The whole sky is grey. I have not even seen one blue spot on the sky	data123854_cmb.txt
12	12:39	CMB	13	1	301.3	299.8	100.3	60.80		data123947_cmb.txt

Table 11: Data from observations of the sky on 07-07-15

8.1 Sky observations

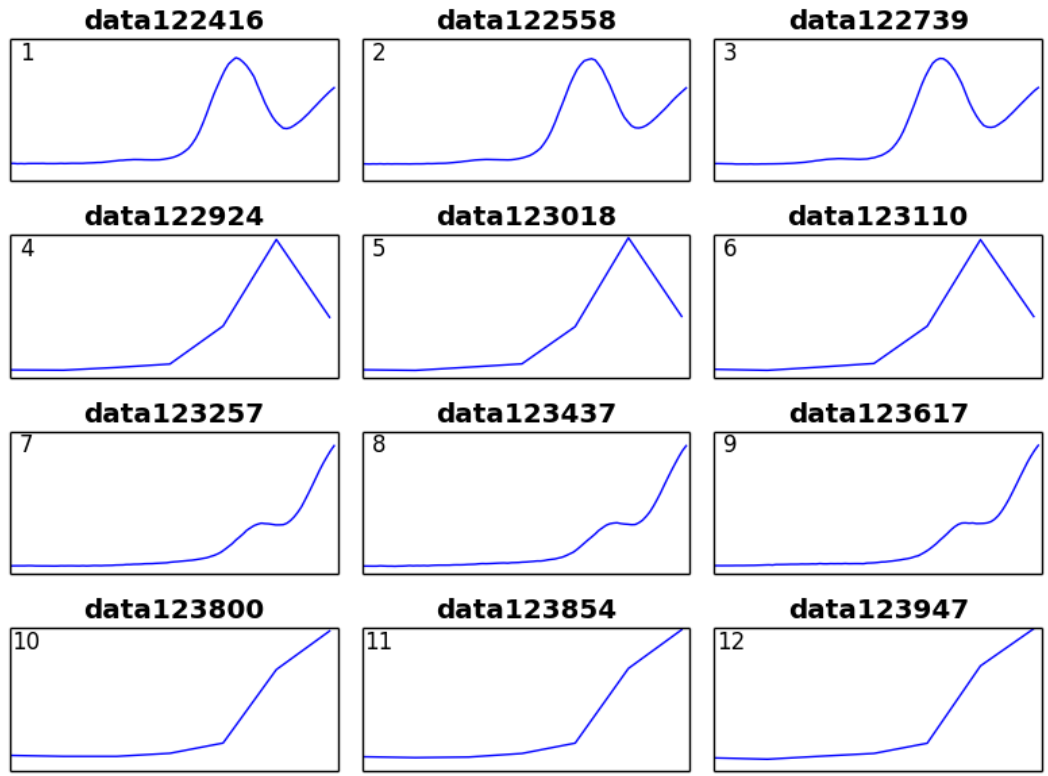
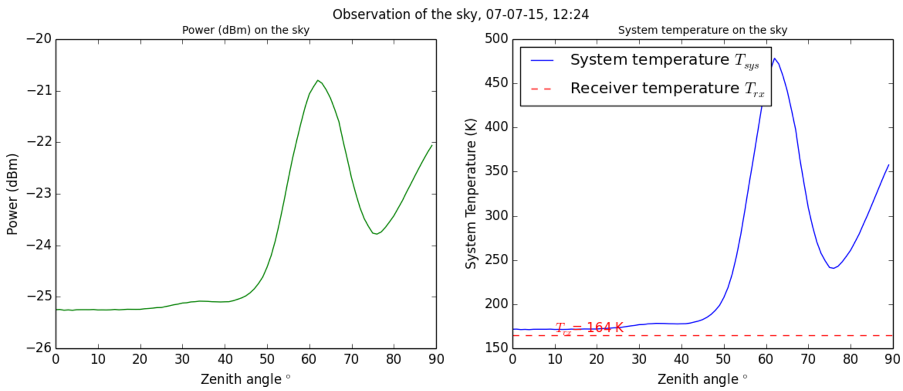
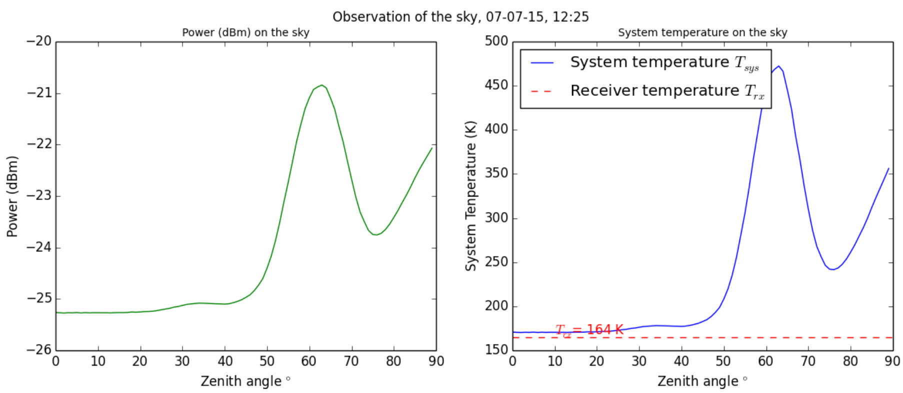
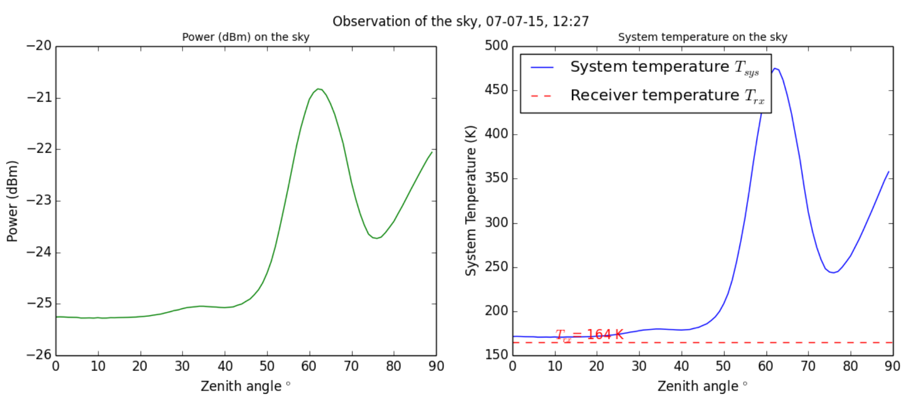
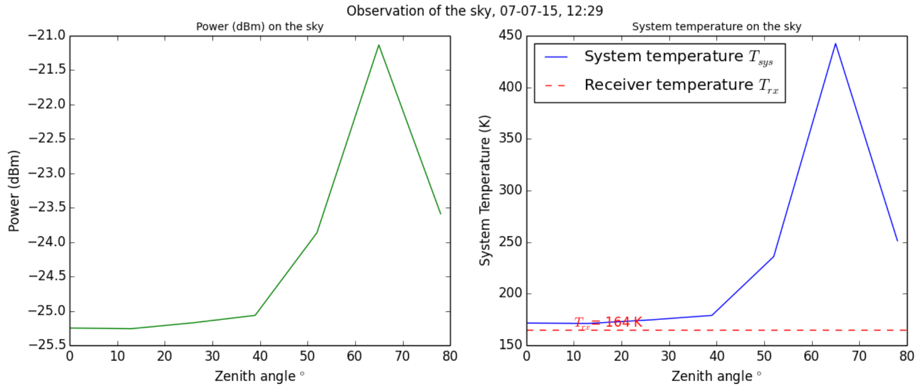


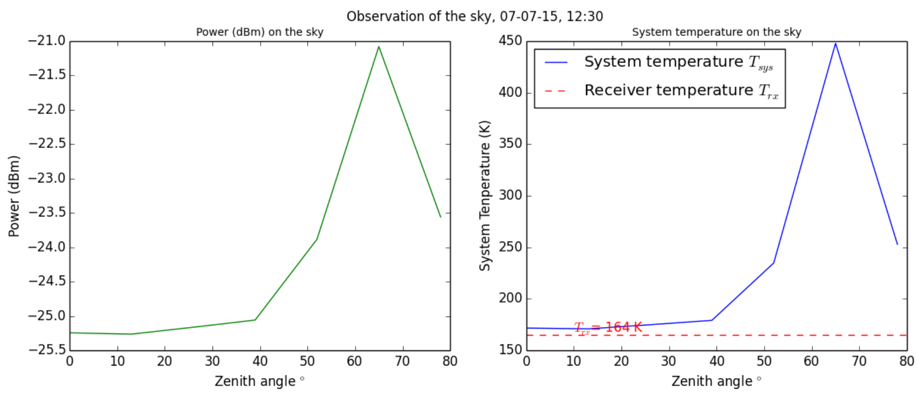
Figure 8: Overview measurements 07-07-2015.

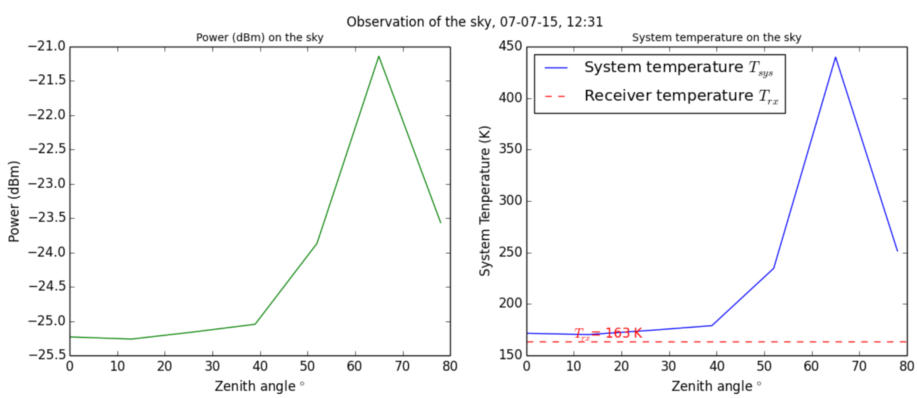

Observation of the sky, 07-07-15, 12:24
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
= 164 K
Zenith angle °

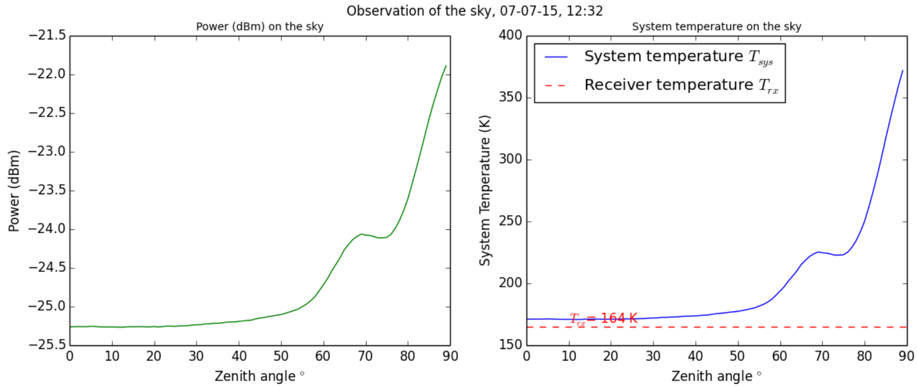

Observation of the sky, 07-07-15, 12:25
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
= 164 K
Zenith angle °

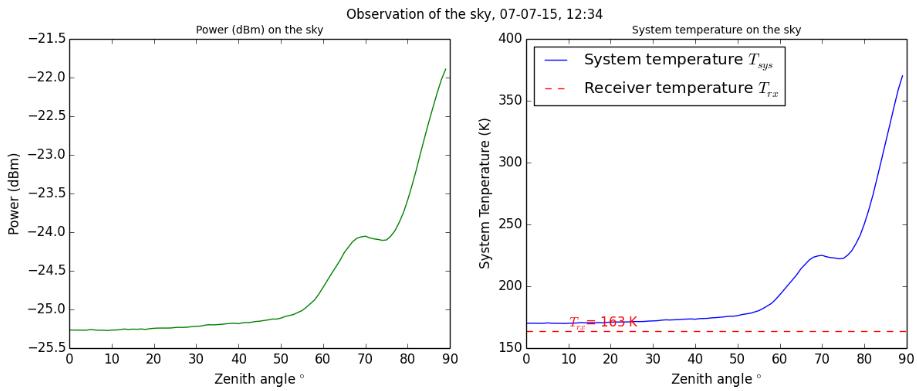

Observation of the sky, 07-07-15, 12:27
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
= 164 K
Zenith angle °

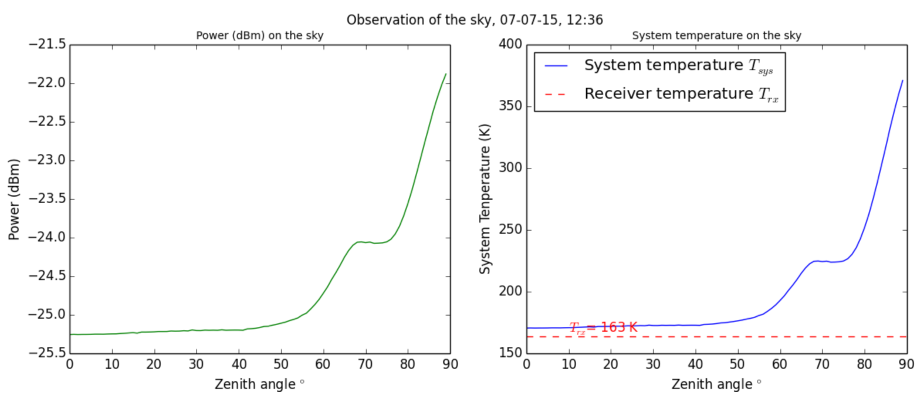

Observation of the sky, 07-07-15, 12:29
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 164 K
Zenith angle °

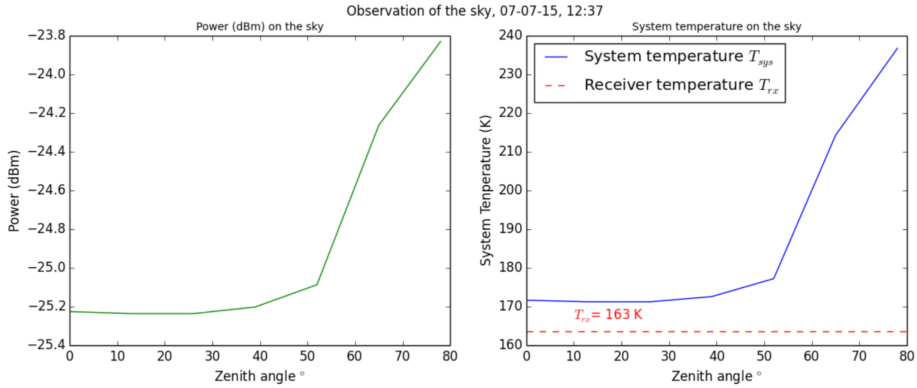

Observation of the sky, 07-07-15, 12:30
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 164 K
Zenith angle °

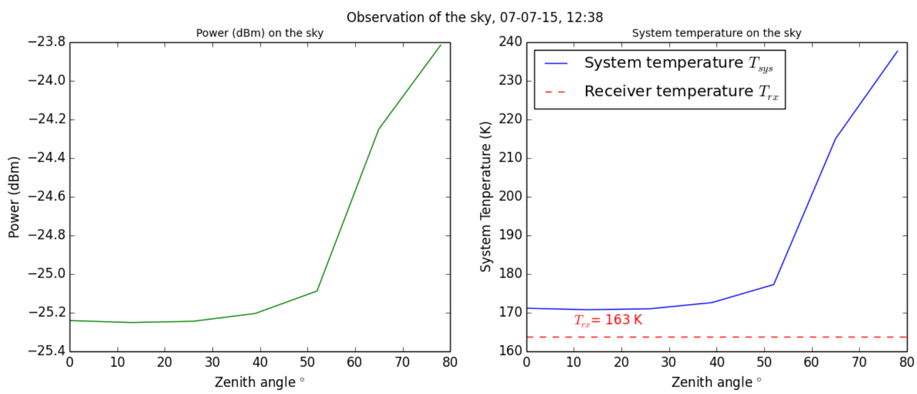

Observation of the sky, 07-07-15, 12:31
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 163 K
Zenith angle °

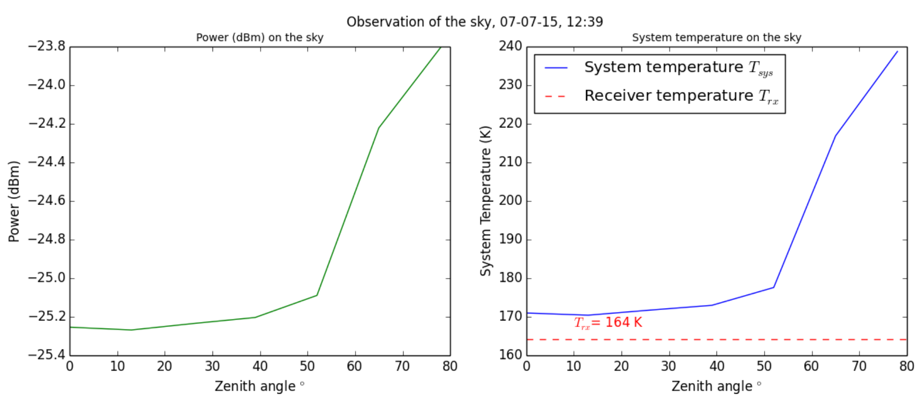

Observation of the sky, 07-07-15, 12:32
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 164 K
Zenith angle °


Observation of the sky, 07-07-15, 12:34
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 163 K
Zenith angle °


Observation of the sky, 07-07-15, 12:36
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 163 K
Zenith angle °


Observation of the sky, 07-07-15, 12:37
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 163 K
Zenith angle °


Observation of the sky, 07-07-15, 12:38
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 163 K
Zenith angle °


Observation of the sky, 07-07-15, 12:39
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 164 K
Zenith angle °

8.2 Hot-Coldload measurements

	Time	Amount measurements [39]	N [40]	T_{atm} (K)	T_{hot} (K)	T_{cold} (K) [41]	P_{hot} (dBm)	P_{cold} (dBm)	T_{rec} (K)	Y-factor$_{real}$ [42]	Y-factor$_{sys}$	Gain$_{sys}$ (dB)	Remarks	File name
1	12:17	20	1	302.1	300.72	97.62	-20.91	-23.33	164.50	1.9252	1.7545	61.31	The cold load was not standing perfect under the frame, which could cause some bad data.	data121708.txt
2	12:42	20	1	300.6	299.69	99.16	-20.92	-23.38	164.03	1.9227	1.7619	61.26		data124209.txt

Table 12: Data from calibration measurements on 07-07-15

9 Observations 07-09-15

Today the sky was not nice for observations. There were a lot of clouds on the sky. It had been raining that night, therefore the temperature was better than the previous days. There was a little breeze. Due to time pressure I decides to put the telescope outside. At the beginning of the observations it was raining a bit. I was standing on the balcony of SRON and was looking in the direction where the telescope aims directly between the Kapteyn and the Duisenberg building, in a South-West direction. My coordinates were $53°14'25.5"N6°32'06.9"E$ (Google Maps).

9.1 Sky observations

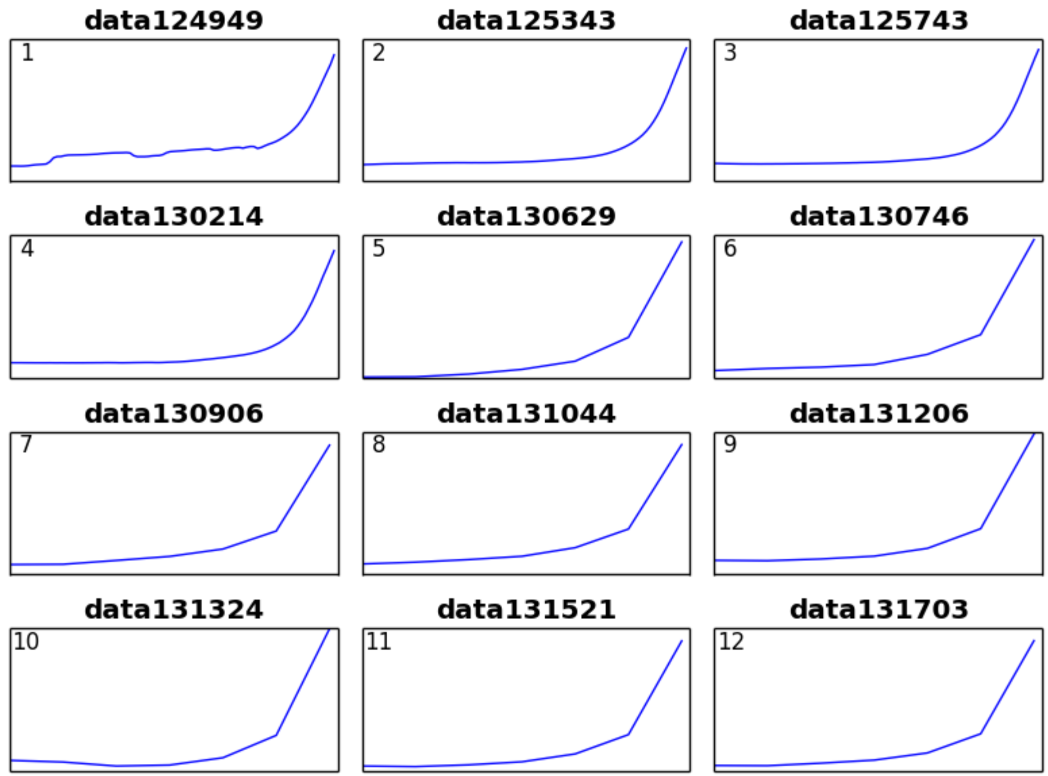
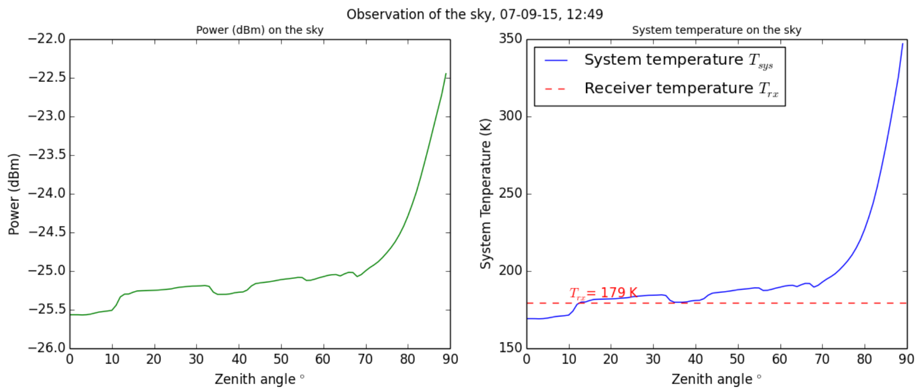
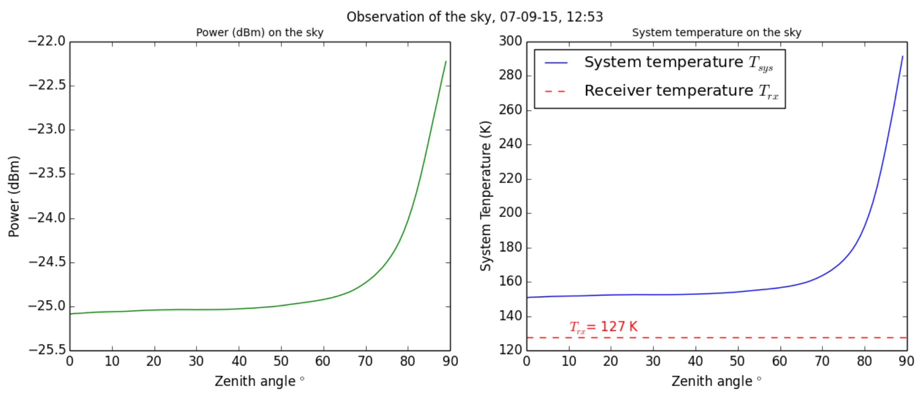


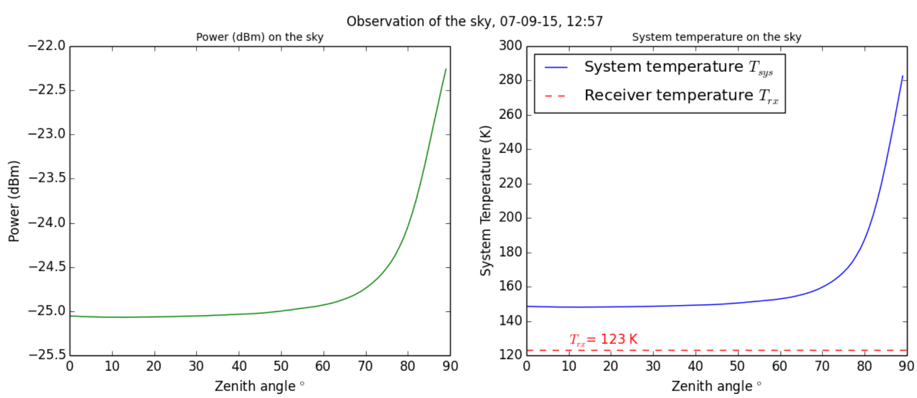
Figure 9: Overview measurements 07-09-2015.

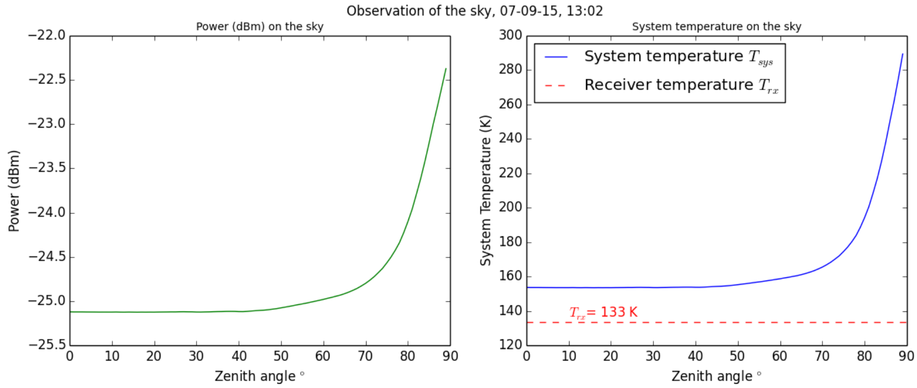
	Time	Observation of..	Measure size (°)	N [43]	T_{atm} (K)	T_{hot} (K)	T_{cold} (K) [44]	Gain (dB)	Description sky	File name
1	12:49	Opacity	1	128	290.0	289.7	73.0	60.54	Cloud appearing on the angles $0° < z < 20°$. Until an angle of 30° cloud become less opaque. Till 80° the sky is blue and again at $80° < z < 90°$ there are clouds located.	data124949_tau.txt
2	12:53	Opacity	1	128	289.5	289.1	96.1	61.52	Cloud appearing on the angles $0° < z < 15°$. Until an angle of 30° cloud become less opaque. Till 80° the sky is blue and again at $80° < z < 90°$ there are clouds located.	data125343_tau.txt
3	12:57	Opacity	1	128	291.1	290.1	99.7	61.61	Cloud appearing on the angles $0° < z < 20°$. In the range $20° < z < 75°$ the sky is cloudless. At an angle of 75° the sky is cloudy.	data125743_tau.txt
4	13:02	Opacity	1	256	290.8	292.8	97.0	61.40	Cloud appearing on the angles $0° < z < 15°$. In the range $20° < z < 60°$ the sky is cloudless, with every now and then a little cloud passing by. Until an angle of 75° the sky is blue and from that angle until the horizon the sky gets cloudy.	data130214_tau.txt
5	13:06	CMB	13	512	290.9	294.9	64.9	64.93	Every 20° the sky is changing.	data130629_cmb.txt
6	13:07	CMB	13	512	290.9	294.9	68.6	60.23		data130746_cmb.txt
7	13:09	CMB	13	512	291.0	294.5	71.4	60.49		data130906_cmb.txt
8	13:10	CMB	13	256	290.7	293.0	85.5	60.90	Clouds are just like dots on the sky.	data131044_cmb.txt
9	13:12	CMB	13	256	289.9	291.2	90.7	61.23		data131206_cmb.txt
10	13:13	CMB	13	256	290.1	292.0	92.9	61.21		data131324_cmb.txt
11	13:15	CMB	13	1024	290.7	293.8	84.5	60.93		data131521_cmb.txt
12	13:17	CMB	13	1024	290.3	292.0	84.9	60.93		data131703_cmb.txt

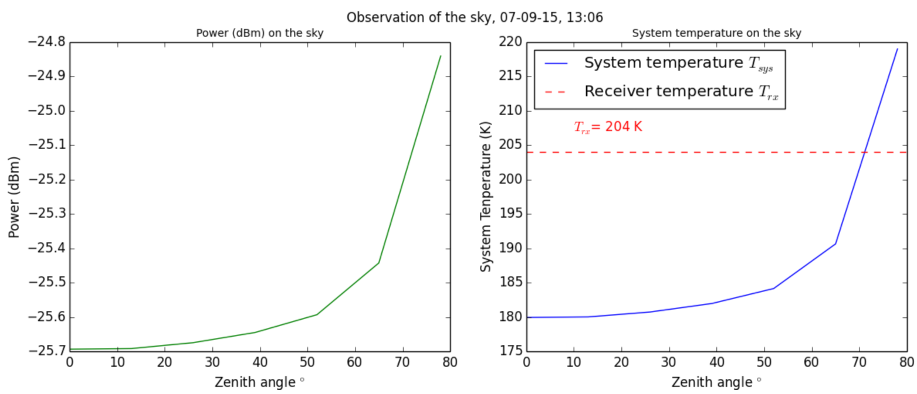
Table 13: Data from observations of the sky on 07-09-15

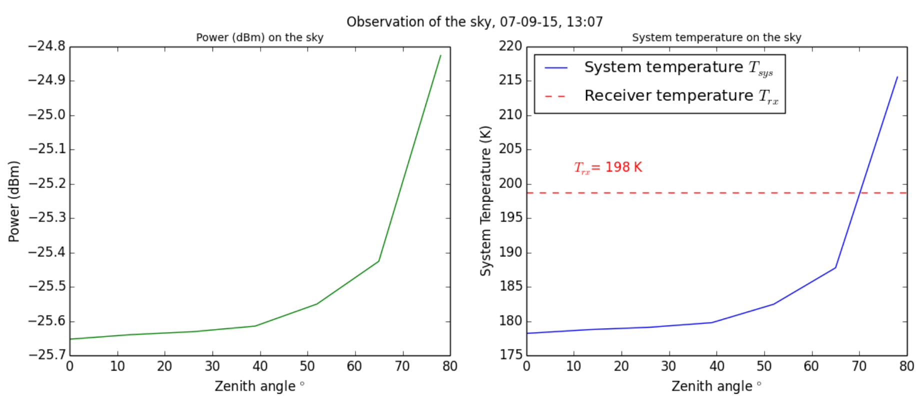

Observation of the sky, 07-09-15, 12:49
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Temperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 179 K
Zenith angle °

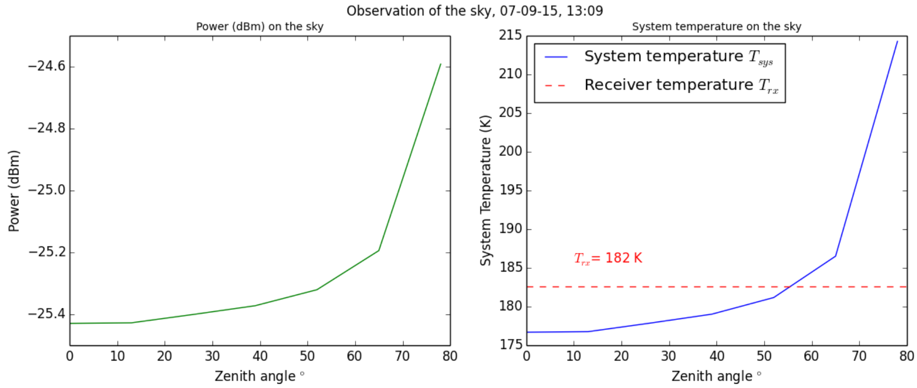

Observation of the sky, 07-09-15, 12:53
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Temperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 127 K
Zenith angle °

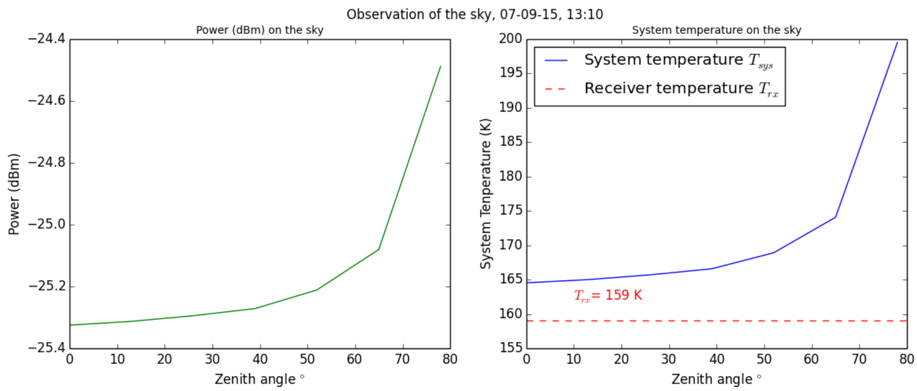

Observation of the sky, 07-09-15, 12:57
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Temperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 123 K
Zenith angle °

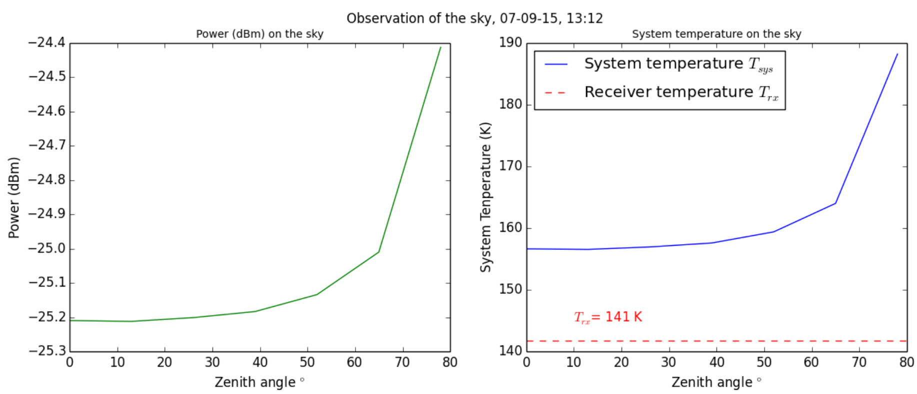

Observation of the sky, 07-09-15, 13:02
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 133 K
System Tenperature (K)
Zenith angle °

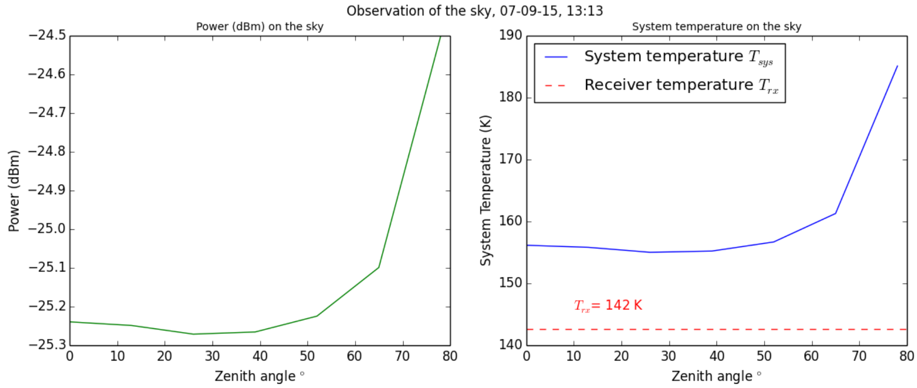

Observation of the sky, 07-09-15, 13:06
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 204 K
System Tenperature (K)
Zenith angle °

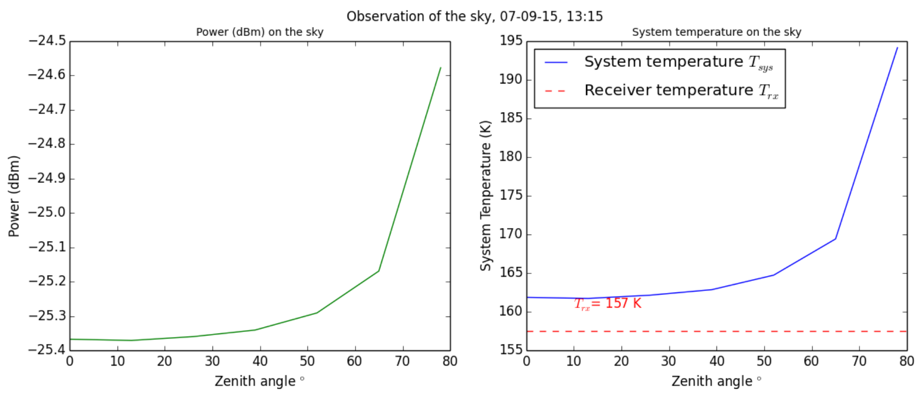

Observation of the sky, 07-09-15, 13:07
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx} = 198 K
System Tenperature (K)
Zenith angle °

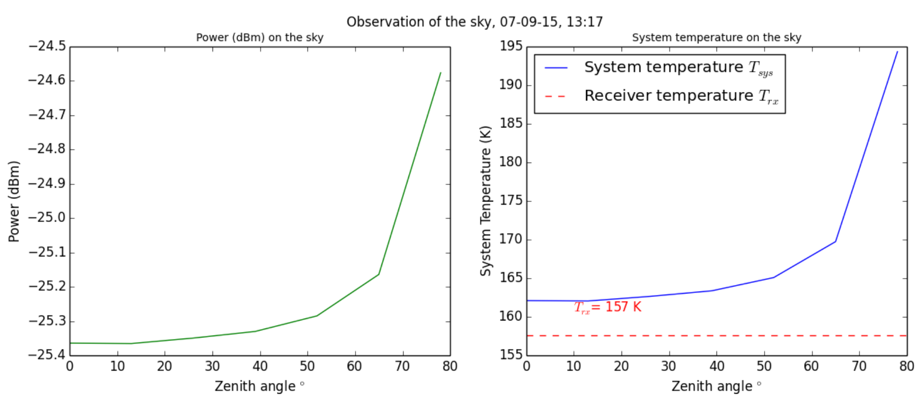

Observation of the sky, 07-09-15, 13:09
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 182 K
Zenith angle °


Observation of the sky, 07-09-15, 13:10
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 159 K
Zenith angle °


Observation of the sky, 07-09-15, 13:12
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Tenperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 141 K
Zenith angle °


Observation of the sky, 07-09-15, 13:13
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
System Tenperature (K)
T_{rx}= 142 K
Zenith angle °


Observation of the sky, 07-09-15, 13:15
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
System Tenperature (K)
T_{rx}= 157 K
Zenith angle °


Observation of the sky, 07-09-15, 13:17
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
System Tenperature (K)
T_{rx}= 157 K
Zenith angle °

9.2 Hot-Coldload measurements

	Time	Amount measurements [45]	N [46]	T_{atm} (K)	T_{hot} (K)	T_{cold} (K) [47]	P_{hot} (dBm)	P_{cold} (dBm)	T_{rec} (K)	Y-factor$_{real}$ [48]	Y-factor$_{sys}$	Gain$_{sys}$ (dB)	Remarks	File name
1	12:41	20	128	289.7	290.14	97.62	-20.92	-23.38	154.55	1.9218	1.8472	61.18		data124117.txt

Table 14: Data from calibration measurements on 07-09-15

10 Observations 07-10-15

Today was the second and last day where I was able to observe the sky. Again it was not a perfect day for zenith opacity and CMB temperature observations. Although, according to this data I can investigate whether it is possible to observe a zenith opacity which makes sense, when observing without having ideal weather conditions. There were a lot of clouds on the sky.Again there was a little breeze present, and it seemed to be a bit warmer than yesterday. Luckely today there was not any rain present. Again standing on the balcony of SRON and looking in the direction where the telescope aims directly between the Kapteyn and the Duisenberg building, order to be able to investigate whether I would receive a difference in the system temperature with respect to yesterday. This should be the case according to the changing gain of the telescope and my fixed calibration. My coordinates were 53°14′25.5” N6°32′06.9” E (Google Maps).

	Time	Observation of..	Measure size (°)	N [49]	T_{atm} (K)	T_{hot} (K)	T_{cold} (K) [50]	Gain (dB)	Description sky	File name
1	13:16	Opacity	1	256	293.15	295.35	92.0	61.10	During the observations clouds were moving quick.	data131611_tau.txt
2	13:20	Opacity	1	256	293.17	295.02	92.3	61.16	At the zenith there was not any cloud present	data132009_tau.txt
3	13:24	Opacity	1	256	293.0	294.64	93.5	61.22		data132407_tau.txt
4	13:28	CMB	13	256	293.82	295.10	93.3	61.19		data132804_cmb.txt
5	13:29	CMB	13	256	293.79	295.17	92.7	61.20		data132912_cmb.txt
6	13:30	CMB	13	256	293.28	294.93	93.3	61.20		data133020_cmb.txt

Table 15: Data from observations of the sky on 07-10-15

10.1 Sky observations

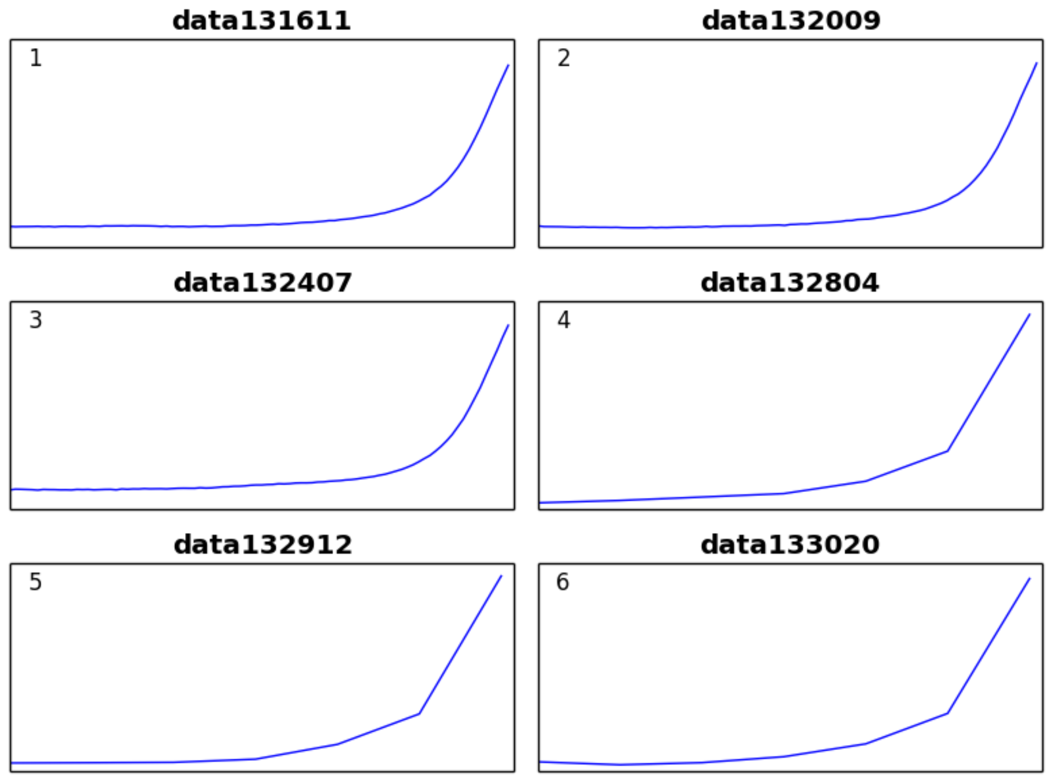
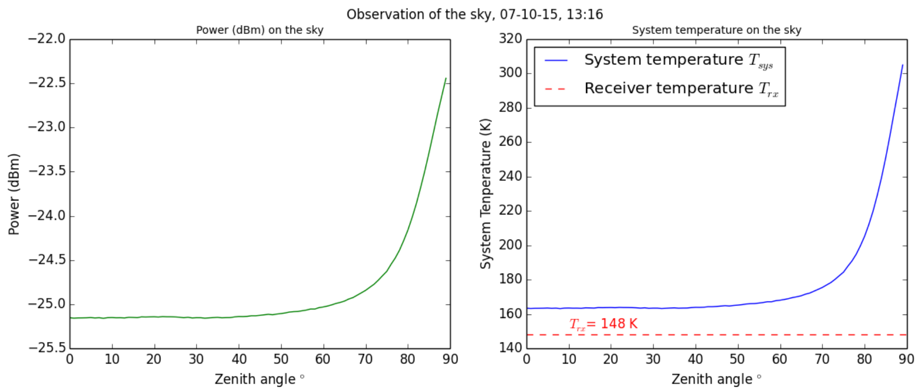
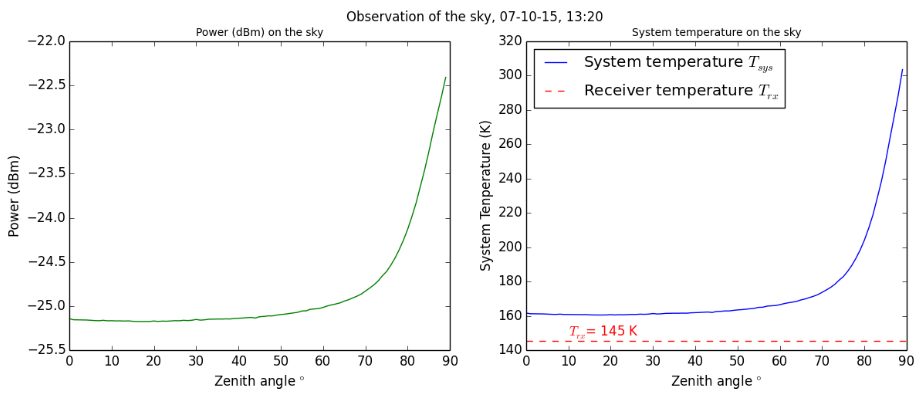
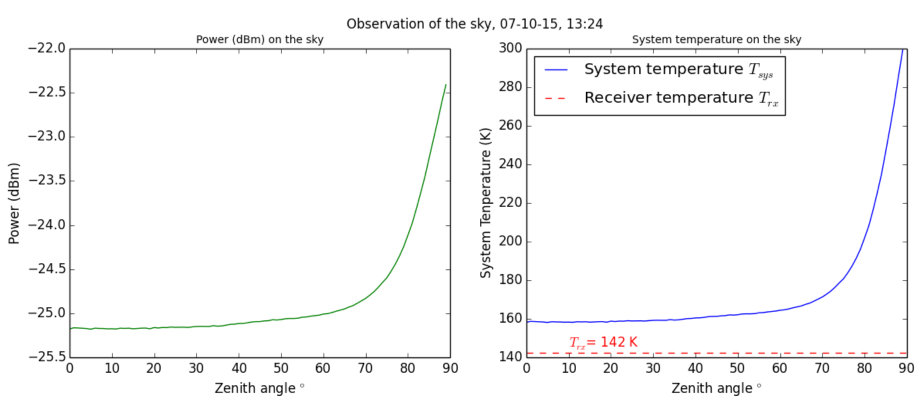
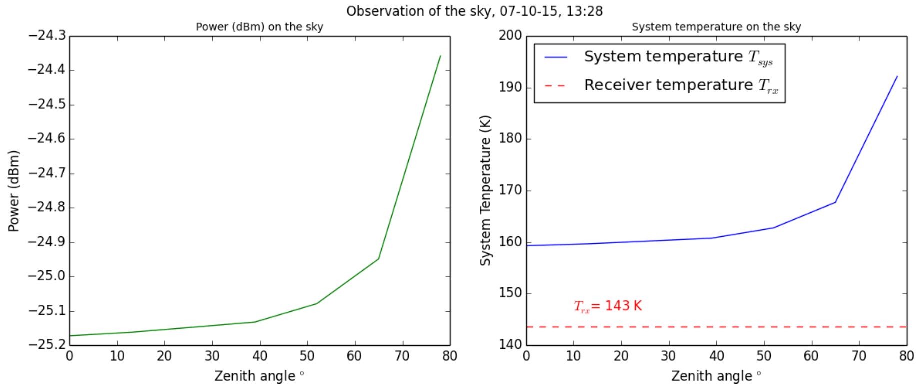


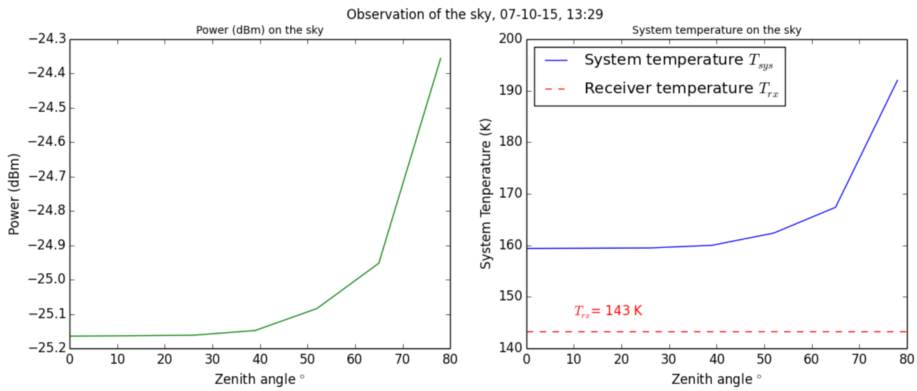
Figure 10: Overview measurements 07-10-2015.

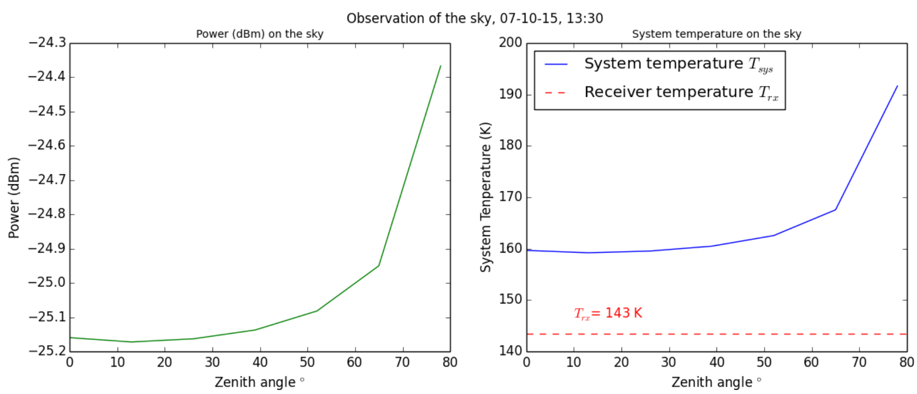

Observation of the sky, 07-10-15, 13:16
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Temperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 148 K
Zenith angle °


Observation of the sky, 07-10-15, 13:20
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Temperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 145 K
Zenith angle °


Observation of the sky, 07-10-15, 13:24
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System Temperature (K)
System temperature T_{sys}
Receiver temperature T_{rx}
T_{rx}= 142 K
Zenith angle °


Observation of the sky, 07-10-15, 13:28
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
System Tenperature (K)
T_{rx}= 143 K
Zenith angle °


Observation of the sky, 07-10-15, 13:29
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
System Tenperature (K)
T_{rx}= 143 K
Zenith angle °


Observation of the sky, 07-10-15, 13:30
Power (dBm) on the sky
Power (dBm)
Zenith angle °
System temperature on the sky
System temperature T_{sys}
Receiver temperature T_{rx}
System Tenperature (K)
T_{rx}= 143 K
Zenith angle °

10.2 Hot-Coldload measurements

	Time	Amount measurements [51]	N [52]	T_{atm} (K)	T_{hot} (K)	T_{cold} (K) [53]	P_{hot} (dBm)	P_{cold} (dBm)	T_{rec} (K)	Y-factor$_{real}$ [54]	Y-factor$_{sys}$	Gain$_{sys}$ (dB)	Remarks	File name
1	12:53	20	128	293.46	295.49	93.27	-20.77	-23.45	143.48	1.9899	1.8541	61.53		data125324.txt
2	13:31	20	128	295.17	295.63	91.97	-20.79	-23.48	146.01	1.9218	1.8558	61.45		data133127.txt

Table 16: Data from calibration measurements on 07-10-15