



# UNIVERSITY OF GRONINGEN Kapteyn Astronomical Institute Bachelor Research Project

# Back-end and Mechanics of a Pickett-Potter Horn Telescope at 11GHz

Author: Maik Zandvliet Supervisors: Prof. Dr. Andrey Baryshev Dr. Ronald Hesper Dr. John P. McKean

July 15, 2015

This bachelor thesis covers the design and construction of the back-end and frame of a Pickett-Potter horn telescope at 11 GHz to observe the cosmic microwave background. The back-end of the telescope contains two amplifiers and a band pass filter. The choice of these components is elaborated in the form of theory and experiments. The main factor in choosing an amplifier relied on the effective noise temperature. The construction of the frame for the telescope entailed decisions on functionality, size, positioning of extra devices needed for power, calibration and slewing to create a fully functional telescope.

# Contents

1.	Introduction	5
	1.1. The Field of Radio Astronomy	5
	1.2. The Cosmic Microwave Background	5
	1.3. The Telescope $\ldots$	5
2.	Horn Design	6
	2.1 Types of Horns	6
	2.2. Our Telescope Design	6
		Ū
3.	Noise	7
	3.1. Describing Noise	7
	3.1.1. Probability Density Function	7
	3.1.2. Spectral Density Function	8
	3.1.3. Autocorrelation Function	8
	3.1.4. Summary	8
	3.2. Classification of Noise	9
	3.2.1. White Noise	9
	3.2.2. Flicker Noise	9
	3.2.3. Random Walk Noise	10
	3.2.4. Phase and Frequency Noise	10
_		
4.	Back-end	10
	4.1. Overview of Receiver Components	10
	4.1.1. Amplifiers	11
	4.1.2. Filters $\ldots$	13
	4.1.3. Attenuators $\ldots$	13
	4.2. Testing the Amplifiers	14
	4.2.1. Back-end Noise temperature	14
	4.2.2. Amplifier with DC Block	17
	4.3. Checking Linearity	19
	4.4. Chain Order	23
Б		24
5.	5.1 Introduction to Allan Variance	24 94
	5.1.1 Time Domain Stability	24
	5.1.1. Time Domain Stability	20 96
	5.2. Anali variance for the relescope	20
6.	Mechanics	29
	6.1. Securing Back-end and Horn	29
	6.2. Stability of Telescope	29
	6.2.1. Frame of the Telescope: Plan A	29
	6.2.2. Frame of the Telescope: Plan B	31
	6.2.3. Final Frame with Motor and Horn	32
	6.3. Hot and Cold Load	33
	6.3.1. Why a Hot and Cold Load?	33
	6.3.2. Making the Hot and Cold Load	33
		-

7.	Calibration of the Telescope	36
	7.1. Stability of Hot and Cold Load	36
	7.2. Receiver Temperature of the Telescope	40
	7.3. Error in Receiver Temperature	42
8.	Improvements	44
9.	Conclusion	45
10	. Acknowledgments	45
11	References	46
Α.	Allan Variance Script	47
В.	List of Parts	50
С.	The Script for Data Reduction	51

# 1. Introduction

### 1.1. The Field of Radio Astronomy

Radio astronomy is a wide and varied subfield of astronomy, where celestial objects are studied at radio frequencies. The first radio observation was made in the 1930s, when Karl Jansky observed radiation from the Milky Way and today it is seen as the birth of radio astronomy. In Figure 1.1 Jansky can be seen building his telescope.

Long before Jansky observed the Milky Way, physicists were already speculating if radio waves could be observed from celestial objects. It was not until the discovery of the 21-cm line of hydrogen, quasars, pulsars and the cosmic microwave background (CMB) in the 1950s and 1960s that the importance of the discovery of Jansky became apparent.

Today, radio astronomy is a complete field of astronomy. It opened new detection techniques to study the cosmos. One of the big discoveries made through the detection of electromagnetic radiation at radio wavelengths is the CMB.

### 1.2. The Cosmic Microwave Background

The cosmic microwave background is the radiation left over from the epoch of recombination



Figure 1.1: Karl Jansky makes adjustments to his antenna, used to identify radio waves from beyond the Earth for the first time. Image source: https://upload.wikimedia. org/wikipedia/en/c/ce/ Karl\_Guthe\_Jansky\_radio\_ telesacope.jpeg

after the Big Bang. It was first discovered by Arno Penzias and Robert Wilson in 1964. They accidentally discovered some unknown flux on top of the flux coming from Cassiopeia A, this flux was later determined to correspond to a temperature of  $2.72548 \pm 0.00057$  K (Fixsen, 2009).

The CMB was considered a landmark test for the Big Bang model of the universe. Radio astronomy is uniquely suited for observing the CMB and has created virtually a new subject of precision cosmology.

### 1.3. The Telescope

The focus of this thesis is the construction of the back-end and the frame of the telescope. The telescope will be used to observe the CMB at an observing frequency of 11 GHz and will be part of the course Radio Astronomy given by Dr. John McKean at the Kapteyn Astronomical Institute of the University of Groningen.

The research project is conducted together with Bram Lap, Willeke Mulder and Frits Sweijen, each having a different subproject. Bram Lap has designed, optimized and build the horn of the telescope (Lap, 2015), Willeke Mulder takes into account the atmosphere, how we have to incorporate it in the observations, has investigated calibration strategies and has done the data reduction measurements to observe the CMB (Mulder, 2015). Frits Sweijen has created the software to operate the telescope and investigated other celestial sources that could be observed with the radio telescope (Sweijen, 2015). This research project will refer to their research projects for more detailed information regarding certain phases of the telescope.

# 2. Horn Design

This chapter will be a brief summary of the horn design. A more detailed description can be found in Lap (2015).

# 2.1. Types of Horns

In order to make a horn, it is important to decide what type of horn is suited for the observation. An important feature is the wavelength of the observation and required field-of-view. This generally sets the size of the horn. A horn can have several designs; rectangular, diagonal, circular and many variations on these. To investigate which design was the best option for our telescope, a Python script was created that plots beam patterns for different optimal designs. At this stage we were looking at different observing frequencies, 4, 8 and 11 GHz. These frequencies were taken into account when creating the optimal beam patterns, they are created from the theoretical electromagnetic equation for the corresponding design.

The CMB will be the main target of the telescope. To observe the CMB, a higher observing frequency is more desirable, because it follows a black body whose brightness goes like  $B_{\nu} \propto \nu^2$  at low frequencies, also known as the Rayleigh-Jeans limit, more information can be found in Mulder (2015). For this reason and taking into account the beam patterns, the design was chosen to be a circular horn and the observing frequency is 11 GHz.

A circular horn design can vary in shape. P. D. Potter presented a new horn design to be used at ultra high frequencies, that he published in 1963. His horn design featured an equal beamwidth in all planes, complete phase center coincidence and at least 30 dB sidelobe suppression in the electric plane. His work can be found in Potter (1963). The horn design by P. D. Potter is the basis of another variation: the Pickett-Potter horn. This horn design has a smooth conical shape with a single step at the throat and was presented by Pickett et al. (1984).

# 2.2. Our Telescope Design

The design presented by Pickett et al. (1984) is the design used for our telescope, which features the conical shape with a single step. A more detailed description and optimization can be found in Lap (2015). A schematic design of the horn can be seen in Figure 2.1.



Figure 2.1: Blueprint of the horn as designed by Lap (2015).

# 3. Noise

# 3.1. Describing Noise

In signal processing, noise is an unwanted, random and general unknown signal always present in electronic devices. It is the opposite of deterministic signals: a signal whose value at any future time can be exactly predicted. There are five statistical quantities that are commonly used to estimate the behavior of random signals, these quantities are: mean, standard deviation, probability density function, power spectral density and autocorrelation function (Bentley, 2005). Noise is sometimes expressed as a equivalent temperature, the noise temperature, which is not necessarily a physical temperature. It is important to first present these quantities because the noise of our telescope system is what sets the precision of the measurement of the CMB.

#### 3.1.1. Probability Density Function

The probability density function, p(y), is a function of a continuous random variable which describes the probability that this variable will take on a given value. For instance, the normal probability density function:

$$p(y) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(y-\bar{y})^2}{2\sigma^2}\right]$$
(1)

where  $\sigma$  is the standard deviation, y is the value, and  $\bar{y}$  is the mean. Equation 1 usually provides a suitable description of the amplitude distribution of random noise signals. The function always has to be normalized since the area under the function has to be unity (Bentley, 2005).

#### 3.1.2. Spectral Density Function

A periodic signal can be represented by a Fourier series, a sum of sine and cosine waves with frequencies that are harmonics of the fundamental frequency. A random signal is not periodic and cannot be expressed by a Fourier series but it does contain a large number of closely spaced frequencies. The power spectral density (PSD), S(f), describes how the power in a random signal is distributed over these frequencies. Internal noise sources in electrical circuits can often be regarded as white noise, this has a uniform PSD over an infinite range of frequencies (Bentley, 2005).

#### 3.1.3. Autocorrelation Function

The autocorrelation function is a method to describe a signal or time series by multiplying it by a delayed version of itself, resulting in the degree by which its value at one time is similar to its value at a certain later time. It is a mathematical tool to find repeating patterns.

The input signal y(t) and a delayed signal  $y(t - \beta)$  are multiplied to give the product waveform  $y(t)y(t - \beta)$ . This new waveform is averaged over time and that value is the autocorrelation coefficient  $R_{yy}$ . When altering the time delay  $\beta$ , the shape of the product changes, resulting in a different value of  $R_{yy}$ . The relation between  $R_{yy}$  and  $\beta$  is the autocorrelation function  $R_{yy}(\beta)$ .

If the signal is defined by a continuous function y(t) in the interval 0 to  $T_0$ , then  $R_{yy}(\beta)$  can be evaluated using equation 2, such that,

$$R_{yy}(\beta) = \lim_{T_0 \to \infty} \frac{1}{T_0} \int_0^{T_0} y(t) y(t-\beta) dt.$$
 (2)

It can be shown that the autocorrelation function of any periodic signal has the same period as the signal itself.

The autocorrelation function is related to the PSD for random signals, these relations are the Wiener-Khinchin relations,

$$R_{yy}(\beta) = \int_0^\infty S(f) \cos(f\beta) df,$$
  
and  $S(f) = \frac{2}{\pi} \int_0^\infty R_{yy}(\beta) \cos(f\beta) d\beta,$  (3)

(Bentley, 2005).

#### 3.1.4. Summary

and

To specify a random signal we need to know:

either <b>probability density func</b> or <b>mean and standard devi</b>	tion $\left  \begin{array}{c} \\ ation \end{array} \right $	to specify amplitude behaviour.	(4)
either power spectral densit	y	to specify frequency behaviour	(5)

8

These quantities can be related by considering the autocorrelation function at zero time delay,  $R_{yy}(0)$ . Using equations 2 and 3 we have,

$$R_{yy}(0) = \lim_{T_0 \to \infty} \frac{1}{T_0} \int_0^{T_0} y(t)^2 dt = \int_0^\infty S(f) df$$
(6)

(Bentley, 2005).

### 3.2. Classification of Noise

Noise can be classified by its physical properties, there are five different types of noise: shot noise, thermal noise, flicker noise, burst noise and avalanche noise. These noise types are difficult to separate, therefore there is an alternative way to describe noise, which is called color that is statistical property. Many "colors" are used to describe noise, some having a real relationship to the real world. White noise is in the middle of a "spectrum" that runs from purple, to blue, to white, to pink, and to red/brown. These colors correspond to powers of the frequency of the power spectrum and when they are modeled they are of the form  $f^{\alpha}$ . The relations between the color and the power of frequency can be seen in Table 3.1.

Color	α
Purple	2
Blue	1
White	0
Pink	-1
$\operatorname{Red}/\operatorname{Brown}$	-2

Table 3.1: Noise color and their proportionality with frequency.

Not all classifications of noise will be discussed, since not all noise types are relevant to the construction of the back-end of our telescope.

### 3.2.1. White Noise

White noise is a random signal with a constant power spectral density, the signal has equal amount of power in any band of a given bandwidth. The main physical sources of noise in electronics (thermal and shot noise), have a white PSD. As that may be, white noise is not pure white noise, it would require to have infinite energy at infinite frequencies.

#### 3.2.2. Flicker Noise

Flicker noise is also called 1/f noise or pink noise; its origin is one of the unsolved problems in physics. It is always present in all active and many passive devices and it is found in many natural phenomena such as nuclear radiation, electron flow through a conductor or even in the environment. There is no exact mathematical model for flicker noise since it is very specific for different devices. However, the inverse proportionality with frequency is almost exactly 1/f for low frequencies, for high frequencies, the noise power is weak but essentially flat (Mancini, 2002).

#### 3.2.3. Random Walk Noise

Random walk noise has a dependence of  $1/f^2$ , it is the kind of noise produced by Brownian motion, therefore it is also known as Brownian noise. As a result, Brownian noise has a lot more energy at lower frequencies than it does at higher frequencies, it decreases power by 6 dB per octave.

#### 3.2.4. Phase and Frequency Noise

Given the different noise sources described above, there is also a distinction between phase and frequency noise. Phase noise is the rapid, short-term, random fluctuations in the phase of a waveform. The phase noise is increased by the noise figure of an amplifier, where the noise figure is the ratio of the input and output signal-to-noise ratios, respectively. An ideal amplifier would amplify both the signal and noise equally. However, a normal amplifier would add noise to the signal. The phase noise is directly proportional to the thermal noise at the input and the noise figure of the amplifier (Dickstein, 2012).

Frequency noise is the noise of the instantaneous frequency (IF). A frequency for a stationary, periodic, infinite duration signal can be decomposed into sinusoidal components, all with frequencies being multiples of the fundamental frequency. However, things are not as simple in the nonstationary case.

In 1937, Carson and Fry argued that IF is a generalization of the definition of constant frequency. It is the rate of change of phase angle at time t. In 1946 Van der Pol approached the problem of finding a definition of IF by analyzing an expression with a time varying amplitude and phase of a simple harmonic motion. This led to the definition of IF given by equation 7,

$$f_i(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt},\tag{7}$$

where  $\phi(t)$  is the phase (Boashash, 1992).

### 4. Back-end

#### 4.1. Overview of Receiver Components

The back-end of a radio telescope is also called the receiver. Although a receiver will also contain a horn, in this thesis when a receiver is referred to, it is meant without the horn. The receiver is a series of components that converts the incoming electromagnetic waves to a signal that is prepared for processing. Such a series of components is usually shown in a block diagram, such a diagram can be seen in Figure 4.1.

Not all of these components are always used for building a receiver. For our telescope only an amplifier and filter are required. These components are explained in more details below.

Mixers are used to lower the frequency of the received signal. This process is useful for two reason. It avoids feedback of amplified signals back into the front end and it can choose a frequency which is easier to deal with. A square law detector has an output voltage that is proportional to the square of the input voltage, therefore making the incoming signal always a positive signal. After this process the signal is usually again amplified. The integrator averages a rapidly varying component with the envelope of the signal varying on timescales that are normally much shorter than on which the average signal power varies. Any unwanted rapid variations in the signal can be suppressed by taking the mean of the detected envelope



Figure 4.1: A block diagram of a typical heterodyne receiver.

over some timescale. Finally, the signal is digitalized by a indicator or recorder.

All these components add noise temperature to the overall noise temperature of an antenna system. The total noise of a entire telescope is called the system temperature,  $T_{sys}$ , which is the sum of several terms. The atmosphere will emit radiation which will be detected by the antenna,  $T_{atm}$ . Noise coming from the ground also contributes to the system temperature, for example buildings and communication devices,  $T_{ground}$ . Of course also the radiation coming from the CMB itself will increase the system temperature,  $T_{CMB}$ . Most of the noise is coming from the receiver system itself, which is called the receiver temperature,  $T_{RX}$ . This leads to the equation for the system temperature,

$$T_{sys} = T_{CMB} + T_{atm} + T_{ground} + T_{RX}.$$
(8)

In this thesis, I discuss the noise coming from the receiver,  $T_{RX}$ .

#### 4.1.1. Amplifiers

Amplifiers are devices that increase the power of an input signal. An amplifier takes energy from a power supply and controls the output signal to match it to the incoming signal only with an increased amplitude. An important characteristic of an amplifier is its gain. Amplifier gain is the ratio of the output and the input of the amplifier. There are three different kinds of amplifier gain: voltage gain, current gain and power gain. This depends on the quantity that is being measured,

Voltage gain
$$(A_v) = \frac{V_{out}}{V_{in}}$$
  
Current gain $(A_i) = \frac{I_{out}}{I_{in}}$  (9)  
Power gain $(A_p) = \frac{P_{out}}{P_{in}} = A_v \cdot A_i.$ 

An important feature of an amplifier is whether it is linear or non-linear. All linear systems will at some point become non-linear. This moment is referred to as the system going into compression or beginning to saturate.

When plotting the output power versus the input power, there is a linear relation for linear amplifiers. However, at some point for all amplifiers a higher input power no longer gives a linear higher output power. The point where the input power causes the amplifier gain to decease by 1 dB from the theoretical response is called the 1-dB compression point. Operation should always happen way below this point in the linear region. The visual concept is shown in Figure 4.2 (Frenzel, 2013).



Figure 4.2: The point where the input power causes the gain to decrease 1 dB from the normal expected linear gain is called the 1-dB compression point, corresponding to a P1db. Image source: Frenzel (2013)

For our telescope we were given four amplifiers that we could use, each amplifying around 30 dB. Two of the amplifiers were leftovers from the Atacama Large Millimeter Array (ALMA) band 9 receiver design, the other two were found in the laboratoriums of the Space Research Organisation Netherlands (SRON). The four amplifiers can be seen in Table 4.1 and Figure 4.3.

Amplifier	S/N	Frequency range (GHz)
AML412LE2411 (ALMA1)	0934-252	4-12
AML412LE2411 (ALMA2)	0934-266	4-12
MITEQ M/N AMF-4S-100120-15	309190	8-12
Amplica Inc AXM554504	103	8-12

Table 4.1: Amplifiers used in experiment, with S/N being the serial number.



Figure 4.3: The four amplifiers which were an option to use for the telescope. From left to right: ALMA1, ALMA2, MITEQ and Amplica Inc.

### 4.1.2. Filters

A filter is a device or process that is designed to remove or reshape all unwanted frequencies from a signal, it only lets the allowed signal through. Filters can be divided into two distinct types: active and passive filters. Active filters have an amplifying component, the incoming signal will be amplified, while a passive filter does not amplify the signal<sup>1</sup>.

At high frequencies (>1 MHz), almost all filters are usually passive filters. They consist of passive components such as inductors (L), resistors (R) and capacitors (C) and are also called LRC filters. In the lower frequency range (1 Hz to 1 MHz), active filters become more important (Mancini, 2002).

Filters are categorized according to the frequency range that the filter blocks or lets through:

- band pass filter: allows a range of frequencies  $\nu_{min} < \nu < \nu_{max}$  to pass through,
- low pass filter: allows a range of frequencies  $\nu < \nu_{max}$  to pass through,
- high pass filter: allows a range of frequencies  $\nu > \nu_{max}$  to pass through,
- band stop filter: eliminates a range of frequencies from the system,
- all pass filter: allows all input frequencies through but changes the phase,

(Wilson et al., 2013).

The telescope is designed to observe at 11 GHz with a bandwidth of 1.05 GHz, this is achieved by using a band pass filter, with a frequency range of  $10.45 \text{ GHz} < \nu < 11.50 \text{ GHz}$ .

### 4.1.3. Attenuators

Attenuators are the opposite of amplifiers. They reduce the power of a signal without distorting its waveform. Attenuators are usually passive devices where the output power is a fraction of the input power and can appear at many positions in the circuit of a radiometer.

Attenuators have a certain attenuation expressed in decibels. A 3 dB attenuator reduces

<sup>&</sup>lt;sup>1</sup>See http://www.electronics-tutorials.ws/

the output signal to one half, 6 dB to one fourth, 10 dB to one tenth, 20 dB to one hundredth and so forth.

During the construction of the telescope, three attenuators were used, having an attenuation of 6 dB, 10 dB and 20 dB. These attenuators can be seen in Figure 4.4.



Figure 4.4: The attenuators used to check linearity of the system. From left to right: 20 dB, 10 dB and 6 dB.

### 4.2. Testing the Amplifiers

#### 4.2.1. Back-end Noise temperature

Electrical components create noise, this is an unwanted signal that is always present in components. It is usually measured in an equivalent temperature, the noise temperature, which is not a physical temperature, but a representation of the noise level. For more information about noise see Section 3.

Noise temperature in a cascade of amplifiers is dominated by the first amplifier. Each amplifier in the cascade is related to the gain of all previous amplifiers and thus the first amplifier has the most contribution to the noise temperature, see Equation 10.

$$T_e = T_{e,1} + \frac{T_{e,2}}{G_1} + \frac{T_{e,3}}{G_1 G_2} + \dots + \frac{T_{e_n}}{G_1 G_2 \dots G_{n-1}}$$
(10)

Amplifier noise temperature can be measured using the Y-factor method. The Y-factor method is a widely used method to determine the internal noise in a device under test (DUT) and therefore the noise figure or effective noise temperature.

The output power of a DUT with a noise source at one temperature and another temperature can be measured, these two powers are defined as  $P_{\text{hot}}[W]$  and  $P_{\text{cold}}[W]$ , respectively. The ratio of these two powers is defined as the Y-factor, Y (Agilent, 2010),

$$Y \equiv \frac{P_{\rm hot}[W]}{P_{\rm cold}[W]}.$$
(11)

Since the noise power is directly related to the noise temperature through Nyquist's noise formula,

$$Y = \frac{T_{\text{hot}}[K]}{T_{\text{cold}}[K]}.$$
(12)

The effective noise temperature,  $T_e$ , of a DUT is given by equation 13.

$$T_e = \frac{T_{\rm hot} - T_{\rm cold}Y}{Y - 1}.$$
(13)

The power meter used in this experiment converts the measured power to dBm. In order to use this we have to rewrite the Y-factor in terms of  $P_{\text{hot}}[\text{dBm}]$  and  $P_{\text{cold}}[\text{dBm}]$ . This can be done by using the relation given in equation 14.

$$P[\text{dBm}] \equiv 10 \log_{10} \left(\frac{P[\text{mW}]}{1\text{mW}}\right). \tag{14}$$

Therefore,

$$Y_{\rm dBm} = 10 \log_{10} \left(\frac{P_{\rm hot}}{P_{\rm cold}}\right) \tag{15}$$

$$= 10 \log_{10} (P_{\text{hot}}) - 10 \log_{10} (P_{\text{cold}})$$
(16)

$$= P_{\rm hot}[\rm dBm] - P_{\rm cold}[\rm dBm]$$
<sup>(17)</sup>

and finally we get for the Y-factor,

$$Y = 10^{Y_{\rm dBm}/10} = 10^{(P_{\rm hot}[\rm dBm] - P_{\rm cold}[\rm dBm])/10}$$
(18)

For this experiment we have that  $T_{\text{hot}}$  is the room temperature of 293 K and  $T_{\text{cold}}$  is the temperature of liquid nitrogen, 77.15 K. Therefore we get for equation 13,

$$T_e = \frac{T_{\rm hot} - T_{\rm cold}Y}{Y - 1} = \frac{293 \text{ K} - 77.15 \text{ K} \cdot Y}{Y - 1}$$
(19)

where Y is given in equation 18.

Using these formulas the effective noise temperature was determined for various possibilities of amplifier setups, where the amplifiers that were used can be seen in Section 4.2.

A 50  $\Omega$  load is used to have a reference that always gives the same amount of noise power at a given temperature. The output power is measured when the load is at room temperature,  $P_{hot}$ . The load is then placed in liquid nitrogen and the output power is measured,  $P_{cold}$ . Following these procedures the effective noise temperature is calculated.

We use a Agilent E4418B Power Meter (Agilent, 2013) to read the output power. The results of the measurements can be seen in Table 4.2. Where the order of the amplifiers can be seen in Figure 4.5. We used two amplifiers since the signal with any amplification is around -85 dB (Sweijen, 2015). To get a signal which is easier to process we want to amplify the signal. Using two amplifiers we get a signal around -25 dB, this level is strong enough power to process.

	Amplica Inc	ALMA1	ALMA2+1
P <sub>hot</sub> (dBm)	$-40.56 \pm 0.02$	$-50.5 \pm 0.02$	$-19.98 \pm 0.02$
$P_{cold}$ (dBm)	$-41.54 \pm 0.02$	$-53.5 \pm 0.02$	$-22.57 \pm 0.02$
Y-factor	$1.25 \pm 0.01$	$1.9\pm0.01$	$1.81\pm0.01$
$\mathbf{T}_{e}$ (K)	$775.53 \pm 27.49$	$139.7\pm2.83$	$187.53 \pm 3.84$
	MITEQ + ALMA1	ALMA1 + MITEQ	
P <sub>hot</sub> (dBm)	$-19.69 \pm 0.02$	$-20.52 \pm 0.02$	
$P_{cold}$ (dBm)	$-22.28 \pm 0.02$	$-23.19 \pm 0.02$	
Y-factor	$1.81 \pm 0.01$	$1.85\pm0.01$	
$\mathbf{T}_{e}$ (K)	$187.53 \pm 3.84$	$177.01 \pm 3.60$	

Table 4.2: Experimental results for the amplifier noise measurements. ' $P_{hot}$  (dBm)' is the output power at room temperature and ' $P_{cold}$  (dBm)' is the output power at liquid nitrogen temperature. With the error being the measurement errors from the power meter.



Figure 4.5: Schematic overview of the amplifier order during the experiment.

The first entry in Table 4.2 is the amplifier combinations. For example ALMA1+MITEQ means that the first entry is ALMA1 and the second entry is MITEQ in Figure 4.5. When only one name is given the second entry was left empty.

Following the ALMA amplifier test, the experimental result was compared to the literature and it was concluded that the ALMA amplifiers had a much higher noise than expected. The higher noise was due to a faulty cable connecting the amplifier with the 50 ohm load. After replacing the cable some measurements were retaken and the results can be seen in Table 4.3.

	ALMA2+1	ALMA2+1	ALMA1+2
P <sub>hot</sub> (dBm)	$-19.79 \pm 0.02$	$-19.85 \pm 0.02$	$-19.94 \pm 0.02$
$P_{cold}$ (dBm)	$-22.97 \pm 0.02$	$-22.93 \pm 0.02$	$-22.93 \pm 0.02$
Y-factor	$2.08\pm0.01$	$2.03\pm0.01$	$1.99\pm0.01$
$\mathbf{T}_{e}$ (K)	$122.77 \pm 2.51$	$131.93 \pm 2.68$	$140.73 \pm 2.85$
	MITEQ+ALMA1	ALMA1+MITEQ	ALMA1+MITEQ
P <sub>hot</sub> (dBm)	$\mathbf{MITEQ} + \mathbf{ALMA1}$ $-20.20 \pm 0.02$	$\frac{\mathbf{ALMA1} + \mathbf{MITEQ}}{-19.75 \pm 0.02}$	$\frac{\mathbf{ALMA1} + \mathbf{MITEQ}}{-19.75 \pm 0.02}$
P <sub>hot</sub> (dBm) P <sub>cold</sub> (dBm)	$\begin{array}{c} \textbf{MITEQ+ALMA1} \\ -20.20 \pm 0.02 \\ -23.52 \pm 0.02 \end{array}$	ALMA1+MITEQ -19.75 $\pm$ 0.02 -22.85 $\pm$ 0.02	ALMA1+MITEQ -19.75 $\pm$ 0.02 -22.83 $\pm$ 0.02
P <sub>hot</sub> (dBm) P <sub>cold</sub> (dBm) Y-factor	$\begin{array}{c} \textbf{MITEQ+ALMA1} \\ -20.20 \pm 0.02 \\ -23.52 \pm 0.02 \\ 2.15 \pm 0.01 \end{array}$	ALMA1+MITEQ -19.75 $\pm$ 0.02 -22.85 $\pm$ 0.02 2.03 $\pm$ 0.01	ALMA1+MITEQ -19.75 $\pm$ 0.02 -22.83 $\pm$ 0.02 2.02 $\pm$ 0.01

Table 4.3: Experimental results for the amplifier noise measurements with a new cable. ' $P_{hot}$  (dBm)' is the output power at room temperature and ' $P_{cold}$  (dBm)' is the output power at liquid nitrogen temperature.

### 4.2.2. Amplifier with DC Block

Amplifiers are designed to work for certain frequency ranges. The frequency ranges of our amplifiers can be seen in Table 4.1. An amplifier has a capacitor to keep DC voltages away from the input and output. If the capacitor is not working, then the amplifier will let more power through than is wanted. This can be tested by placing a DC block at the output of the amplifier. A DC block works the same as a capacitor, it blocks a signal for a certain frequency range. The DC block used to measure the amplifier is an INMET 8037<sup>2</sup>.

The idea is the following: measure the output power of the system without the DC block, this is the reference. Then place the DC block at the output of the last amplifier and measure the output power, do the same for the middle amplifier. If the output powers are different compared to the reference, the capacitor of the amplifier itself is broken. The results can be seen in Table 4.4.

Measurement	Power output (dBm)	Scheme
Reference	$-6.53 \pm 0.02$	Figure 4.6
1	$-6.88 \pm 0.02$	Figure 4.7
2	$-6.93 \pm 0.02$	Figure 4.8

Table 4.4: Measurement results for the amplifiers with DC blocks. The schematic schemes for the various measurements can be seen in Figures 4.6, 4.7 and 4.8.

 $<sup>^2 \</sup>mathrm{see}$  Aeroflex and Inmet Inc



Figure 4.6: Schematic scheme for the reference measurement.



Figure 4.7: Schematic scheme for measurement 1.



Figure 4.8: Schematic scheme for measurement 2.

Conferring with the specifications of the DC block, we see that it has an insertion loss of maximal 0.5 dB. From Table 4.4 we see that there is a maximum difference of 0.4 dBm between a measurement and the reference. Thus we can conclude that the amplifiers are working correctly.

## 4.3. Checking Linearity

\_

In order to test the system for linearity we use an attenuator as described in section 4.1.3. Linearity is checked by comparing the output power of the system with the attenuator at the output of the last amplifier and at the input. These powers should be the same for both measurements if the system is linear. The results of the measurements can be seen in Table 4.5.

Measurement	Power output (dBm)	Scheme
Reference	$-6.29 \pm 0.02$	Figure 4.9
1	$-12.83 \pm 0.02$	Figure 4.10
2	$-12.32 \pm 0.02$	Figure 4.11
3	$-12.29 \pm 0.02$	Figure 4.12
4	$-12.71 \pm 0.02$	Figure 4.13

Table 4.5: Results for linearity test. The schematic schemes for the various measurements can be seen in Figures 4.9 to 4.13.



Figure 4.9: Schematic scheme for the reference measurement.



Figure 4.10: Schematic scheme for measurement 1.



Figure 4.11: Schematic scheme for measurement 2.



Figure 4.12: Schematic scheme for measurement 3.



Figure 4.13: Schematic scheme for measurement 4.

Comparing the output powers of measurements 1 and 2, we see that there is a difference of 0.51 dBm, meaning that the system is not linear. These measurements were done using two attenuators of 10 dB and 6 dB in the system. In order to get a smaller difference we replaced the 6 dB attenuator with an 20 dB attenuator and repeated the measurements. These measurements can be seen in Table 4.6.

Measurement	Power output (dBm)	Scheme
Reference	$-20.92 \pm 0.02$	Figure 4.14
1	$-27.05 \pm 0.02$	Figure 4.15
2	$-26.87 \pm 0.02$	Figure 4.16

Table 4.6: Results for linearity test with the replaced 20 dB attenuator. The schematic schemes for the various measurements can be seen in Figures 4.14, 4.15 and 4.16.



Figure 4.14: Schematic scheme for the reference measurement.



Figure 4.15: Schematic scheme for measurement 1.



Figure 4.16: Schematic scheme for measurement 2.

Comparing again the output powers of measurement 1 and 2 of Table 4.6, we see that the difference is now 0.18 dBm. This difference is still too large.

Since we are now amplifying 30 dB and attenuating 30 dB, we decided that we could remove the attenuators and 1 amplifier. The amplifier with the highest noise temperature was removed, this is the ALMA1 amplifier. Again the system was checked for linearity and the results can be seen in table 4.7.

Measurement	Power output (dBm)	Scheme
Reference	$-20.92 \pm 0.02$	Figure 4.17
1	$-30.53 \pm 0.02$	Figure 4.18
2	$-30.48 \pm 0.02$	Figure 4.19

Table 4.7: Results for linearity test with the MITEQ and ALMA2 amplifier. The schematic schemes for the various measurements can be seen in Figures 4.17, 4.18 and 4.19.



Figure 4.17: Schematic scheme for the reference measurement.



Figure 4.18: Schematic scheme for measurement 1.



Figure 4.19: Schematic scheme for measurement 2.

These results give a difference of 0.05 dBm, which is small enough to say that the system is linear.

Given this information we again calculated the noise temperature of the amplifiers, using the same technique as described in Section 4.2.1 and found a system temperature 110.09  $\pm$  2.28 K. The schematic scheme of the final back-end system can be seen in Figure 4.20.



Figure 4.20: Schematic scheme for the final back-end system for which the system temperature is calculated.

### 4.4. Chain Order

The electronic circuit of the telescope contains the following components: the MITEQ and the ALMA2 amplifiers and the band pass filter with a frequency bandwidth of 1.05 GHz. These components were chosen to be the best option following the procedures as described in Section 4.2. The schematic overview of the component layout can be seen in Figure 4.21.



Figure 4.21: The schematic overview of the final components layout of the telescope.

The amplifiers in the chain have to be cooled by a heat sink. This heat sink is an aluminum plate on which the amplifiers and other components are placed. The aluminum plate has to be thin enough to make it not too heavy for the motor to rotate it, but thick enough to make it not too flexible. For this reason an aluminum plate with a thickness of 3 mm was chosen.

All the components are placed on the aluminum plate in the order as in Figure 4.21. The amplifiers had to be connected to a power supply cable. This cable was made to fit on the aluminum plate. The power cable has a connector in order to easily disconnect the amplifiers from the power supply.

All the components are connected via coaxial RF cables (radio frequency cables). These cables are designed to work at radio frequencies, the cables are connect via SMA connectors (SubMiniature version A). These connectors are made to be used on components like amplifiers and filters. Coaxial cables typically consists of inner conducting copper cable, surrounded by a dielectric insulator, that is surrounded by a woven copper shield and protected by an insulating plastic sheath.

The completed circuit can be seen in Figure 4.22, where all the components are connected along with the power head.



Figure 4.22: The back-end: the electronic circuit mounted on the aluminum plate, together with the power head.

# 5. Allan Variance

#### 5.1. Introduction to Allan Variance

The Allan variance or two-sample variance is a technique that relates the expectation value of the standard deviation of frequency fluctuations for any finite number of data samples to the infinite time average value of the standard deviation. Therefore, the Allan variance is useful for measuring the frequency stability in for example clocks, oscillators and amplifiers (Allan, 1966).

This technique was postulated by David W. Allan and published in 1966. The general idea is the following: a data set can be divided into bins based on an averaging time, then take the average of that bin, then take the average difference of the successive bins and square this difference and add them all up. This sum is then divided by the total number of bins. This gives the Allan variance for a given averaging time. The original formula of the Allan variance,  $\sigma^2$ , is:

$$\sigma_y^2(\tau) = \frac{1}{2(M-1)} \sum_{i=1}^{M-1} (y_{i+1} - y_i)^2$$
(20)

where  $y_i$  is the *i*th of *M* fractional frequency values averaged over the measurement sampling interval,  $\tau$ .

The Allan variance is much like the normal variance, but has the advantage for more divergent noise types such as flicker noise and of converging to a value that is independent on the number of samples. The original Allan variance formula has been largely superseded by other variations, such as the overlapping Allan variance or the modified Allan variance.

Repeating the calculation of the Allan variance for different averaging times gives you an

Allan plot, which is usually plotted in a log-log format of the variance versus  $\tau$ . The Allan variance is one of the most common time domain measurements of frequency stability.

#### 5.1.1. Time Domain Stability

The stability of a frequency source is based on the fluctuations in phase and frequency as a function of time. An analysis of the stability uses some type of variance, for example the Allan variance. The most common way is to create a log-log plot with  $\sigma^2$  versus  $\tau$ . It shows the dependence of the stability on the averaging time, the stability value and the type of noise. The power law noise will have a typical slope,  $\mu$ , for different type of noise which are shown in Table 5.1.

Type	$\alpha$	$\mu$
White PM	2	-2
Frequency PM	1	$\sim$ -2
White FM	0	-1
Frequency FM	-1	0
Random Walk FM	-2	1

Table 5.1: Power dependence on  $\sigma(\tau)$  and  $S_y(\tau)$ , PM is Phase Modulated and FM is Frequency Modulated.

The power law dependence given in table 5.1 follows the relation,

$$\sigma_{(\tau)} \sim \tau^{\mu/2}$$
, and  
 $S_y(\tau) \sim f^{\alpha}$ . (21)

(SIM, 1986). A log-log plot of the Allan variance (or deviation) reveals different regions. These regions are different noise types. The slope of the Allan deviation line can identify the amount of averaging needed to remove these noise types. The noise types of an Allan plot can be seen in Figure 5.1.



Figure 5.1: Noise types in an Allan deviation plot on a log-log format. Image source: http: //tf.nist.gov/general/glossary.htm

First we notice that the Allan variance does not make a distinction between white phase noise and flicker phase noise. To see a distinction between white phase noise and flicker phase noise another method is useful, the modified Allan variance. However, the distinction between white phase noise and flicker phase noise is not relevant for our telescope. This is because we are only interested in the Allan time.

At short averaging times, the Allan variance is dominated by the noise in the power sensor. When averaging over longer times, the variance decreases. At some point the variance starts to increase again, this is due to the random walk noise in the sensor. This is the inherent instability in the output of the sensor and you want your measurements to take place before the random walk dominates. This point in averaging time where the random walk takes over is called the Allan time, beyond this point you no longer gain profit with a longer integration time.

### 5.2. Allan Variance for the Telescope

There are several ways of calculating the Allan variance, the way it was calculated in this project is the following,

$$\sigma_A^2(n\tau_0) = \frac{1}{2M} \sum_{k=0}^M \left( \sum_{i=kn}^{(k+1)n} \frac{p_i}{\langle p \rangle} - \sum_{j=(k+1)n}^{(k+2)n} \frac{p_j}{\langle p \rangle} \right)^2$$
(22)

where

$$\langle p \rangle = \frac{1}{N} \sum_{q=0}^{N} p_q.$$
<sup>(23)</sup>

Here N is the number of data points in the measurement, n is the size of the bin and it is an integer,  $\tau_0$  is the minimum time interval and M is the number of bins. For N, n, M we have

the boundary condition such that (M+2)n < N. This method was taken from the ALMA Band 5 Cartridge Output Power Stability Test Procedure (Barkhof, 2015). To simulate the different integration times we take equidistant samples and bin them differently.

The Allan variance was calculated for the electric components shown in Figure 4.21. After writing a Python script that can plot the Allan variance vs time, we get an Allan variance plot which can be seen in Figure 5.2 and the script can be seen in Appendix A.

In Figure 5.2 we see that at first the variance decreases for increasing time, at shorter averaging time the Allan variance is higher. We can see that at a time  $\sim 10$  s the variance is minimum, after that the variance increases again. Thus, the Allan time of the back-end system is around 10 s. This means that we want to make an observation within or as close as possible to 10 s. The minimum is not very distinguishable on the top plot of Figure 5.2, but clearly on the second plot the minimum is at  $\sim 10$  s. Whether or not it will be able to achieve this depends on a lot of variables. The motor used for the telescope will have a limited speed it can run and the Raspberry PI is limited to the speed it can read and store data. Together with the efficiency of the software it is hard to get close to the  $\sim 10$  s.

The 500 s measurement was the first measurement taken of the Allan variance. To see what would happen for longer time measurements the other three data sets were acquired, these plots are shown in Figure 5.2. We can see that the random walk, becomes more clear. All of the data sets were measured with a  $\tau_0$  of 50 ms.

On the first two plots we see that for the first  $\sim 10$  s the variance decreases as  $\tau^{-1/2}$  and for the latter two plots as  $\tau^{-1}$ , corresponding to a white frequency noise and white phase and/or flicker phase noise, respectively. After the first  $\sim 10$  seconds the random walk noise dominates over the other noise types.

With the complete telescope system, it was unfortunately not possible to get an observation within 10 s due to the speed of the motor and the recording system. For example, an observation to measure the Sun takes ~80 s and for the CMB it takes ~30 s, at the moment of writing this thesis. However, for this system is does not matter, since the goal is an accuracy of 10 % for the CMB. When looking at Figure 5.2 we can see that  $\sigma^2$  starts at ~  $4 \cdot 10^{-8}$ . Therefore the integration time of the observations can be longer than 10 s.



Figure 5.2: Allan variance plot for various time measurements. From top to bottom: 500 s, 1000 s, 3000 s, 6000 s. Different noise regions can be distinguished in these plots, such as white phase/frequency noise, flicker phase noise and random walk noise.

# 6. Mechanics

This chapter will cover the construction of the telescope. It will contain considerations to ensure functionality in the most efficient way.

# 6.1. Securing Back-end and Horn

The back-end of the telescope has to be connected to the horn, which needs to be stable enough to ensure a clean observation. To ensure stability, the horn is attached to the backend. The attaching is done by drilling holes in the waveguide and the opening of the horn, at the opening of the horn a total of four holes were drilled to allow the horn to be rotated 90 degrees if needs be. With a small piece of aluminum the waveguide is attached to the back-end and the opening of the horn is connected to a thicker piece of aluminum. The two pieces of aluminum are shown in Figure 6.1a. This way, the horn is stable enough during rotation, but not too stiff that it cannot move at all. Due to temperature fluctuations it is possible that the back-end and horn will fluctuate in size. Therefore the aluminum piece connected to the waveguide is thin and a bit flexible.



(a) Two connecting pieces of aluminum.



(b) Electronic circuit and horn.

Figure 6.1: Figure (a): The two pieces of aluminum connecting the horn and the plate with the components together. Figure (b): The electronic circuit panel and the horn attached using the two pieces of aluminum.

# 6.2. Stability of Telescope

### 6.2.1. Frame of the Telescope: Plan A

The back-end and the horn have to be mounted on a frame. This frame will also house the hot and cold load, for more information about the hot and cold load see Section 6.3.

The first idea for the frame was based on a cold load that was available to us from the beginning of the constructing. This cold load is a round bucket with dimensions of 200x200x210 mm. The idea was to position the horn in a horizontal orientation instead of downward directly into the cold load, that way a mirror can be placed in front of it and the beam pattern will be reflected into the bucket. Below the horn there would be room for the power supplies, power meter and other components. However, this idea results in a long path for the beam pattern to travel to get from the horn to the cold load. A longer path means a larger beam pattern projected on the ground. Therefore the bucket should be placed as close to the horn as possible to minimize this projection. This resulted in a sketch that can be seen in Figure 6.2a. In Figure 6.2b we can see the final design for the frame.



(a) Sketch of the first frame design.

(b) Final design of the frame.

Figure 6.2: Telescope frame designs. Figure (a): The first design is shown in the form of a sketch. Figure (b): The final design of the frame is shown, there are vertical bars in the middle to support the motor. The higher front of the frame is designed to hold the hot load and the mirror for the cold load.

The telescope itself will be placed in the middle of the frame that is shown in Figure 6.2b. It will be mounted on the motor and the motor will be supported by two vertical bars in the middle of the frame.

The frame is made out of aluminum pipes with dimensions of 20x20 mm, that are connected via joints. However, after the construction of the frame it was concluded that it should have been  $\sim 3$  cm higher, in order to allow the horn to rotate a full 360 degrees with enough spacing. A solution was to mount an extra bar of aluminum on top. The actual frame after construction can be seen in Figure 6.3.



Figure 6.3: The constructed frame along with the extra piece of aluminum on top to support the motor and horn.

#### 6.2.2. Frame of the Telescope: Plan B

In Section 6.2.1 the main frame design is discussed. After considering the place and size of the cold load in more detail, it seemed that the cold load was too small to fit the full beam pattern of the horn. There was another cold load available from SRON, it is shown in Figure 6.4. The load was at first larger than was anticipated when designing the frame.



Figure 6.4: On the left the cold load available at the beginning of the construction. On the right the cold load provided by SRON.

Another idea was to make a cold load, this can be done by gluing together a box made out of some sort of polystyrene. Making the load would allow us to fit the load exactly inside the frame already constructed. Be that as it may, the telescope will contain devices that need to be near the frame itself, like power supplies, power meter, Raspberry PI and more. A suitable place for these devices is under the frame, making the cold load from SRON appealing again.

In order to make the cold load from SRON fit, the frame had to be adjusted. To avoid constructing an entire new frame, a second frame was designed to fit under the already existing frame. This under frame would be high enough to allow the cold load to fit under the main frame. It would also be the housing of the devices described above. A picture of the second frame is shown in Figure 6.5a.



(a) The under frame



(b) The under frame with components.

Figure 6.5: Figure (a): The under frame that will be placed under the main frame housing the motor and horn. This frame will house the electronics to operate the telescope. Figure (b): The under frame with the power meter, power supplies and a thermometer.

# 6.2.3. Final Frame with Motor and Horn

The entire frame plus the motor and horn is shown in Figure 6.6.



Figure 6.6: The motor and horn are mounted on the frame, the under frame is mounted under the main frame.

The main and under frame are mounted together using  $8 \ge 40$  mm M6 bolts, along with 8 rings to reduce vibration and  $8 \ge M6$  washers. Holes were drilled into the under frame to make room for rivet nuts. For a full list of parts see Table B.1.

## 6.3. Hot and Cold Load

### 6.3.1. Why a Hot and Cold Load?

The telescope needs to have a hot and cold load. Hot loads consists of a piece of absorber, it has to absorb all of the beam pattern coming from the horn. Cold loads are boxes filled with liquid nitrogen, just like the hot load, the cold load has to absorb all of the beam pattern. The pieces of absorber are conical shaped sheets, which have this shape in order to allow the beam pattern to be reflected as many times as needed before it is completely absorbed.

The hot and cold load are used to measure the receiver temperature of the telescope at each measurement. The receiver temperature is a measure of the noise power at the output of the telescope, taking into account all factors that contribute to the noise power. This receiver temperature is important in order to calculate the system temperature and therefore getting the CMB temperature.

A measurement of the receiver temperature has to be made every time a measurement is taken. This is due to the fact that our telescope it not stable enough to ensure a receiver temperature that is always constant, which will be explained in Section 7.3 and due to the Allan time explained in Section 5.1.

#### 6.3.2. Making the Hot and Cold Load

As is described in Section 6.2, the hot and cold load will be in front of the horn. A mirror is placed in front of the horn when the horn is in a horizontal position. However, when placing the horn horizontal, the mirror had to be placed high enough for the hot load to fit above it. Therefore, the horn will be tilted an angle of 15 degrees downward. This way the mirror can be placed lower and the hot load can be placed above. The mirror is placed at an angle such that the beam will go vertically in the cold load and will be positioned between the frame. The mirror is an aluminum sheet, which will function well enough to act as a mirror at 11 GHz. The mirror is shown in Figure 6.7.





The cold load provided by SRON can again be seen in Figure 6.4. The absorber used for the hot and cold load were provided by ASTRON, the Netherlands Institute for Radio Astronomy. These conical shaped absorber sheets were too tall to have them fully submerged in the liquid

nitrogen for a long period of time. For this reason the conical pyramids were cut one by one to make them smaller. They are then placed on a piece of polystyrene and this is placed in the cold load. The inside walls of the cold load are covered with aluminum foil to make sure all of the beam is getting in the cold load. The completed cold load is shown in Figure 6.8.



Figure 6.8: The completed cold load that goes under the main frame.

The conical sheets are good enough for the hot load. The hot load will be placed above the cold load. Right after the horn is clear rotating from the cold load it will measure the hot load.

The first idea was to place the hot load perpendicular to the center axis of the horn. Although, the hot load would then obstruct the measurement taken when the horn is pointing at zenith. The zenith measurement is important since the opacity is lowest at zenith, for more information about taking into account the opacity and atmosphere see Mulder (2015). A tilted hot load would also be harder to construct than a hot load which is vertical.

After positioning the horn at the correct angle for the hot load, the position for the hot load was determined. The hot load is a sheet of  $\sim 40 \text{ x} \sim 40 \text{ cm}$  of conical absorber and is attached to the higher part of the main frame. This sheet is first attached to a sheet of aluminum, which is attached to the frame. In Figure 6.9 the complete telescope is shown.



Figure 6.9: The complete telescope with all its components and equipment.

# 7. Calibration of the Telescope

### 7.1. Stability of Hot and Cold Load

To make sure a correct receiver temperature is calculated, we want to know how stable the hot and cold load are. The hot load will only vary with the ambient temperature, the cold load will experience fluctuations in the motion and evaporation of the liquid nitrogen. The stability of the cold load is determined by measuring these fluctuations in output power when observing the hot and cold load for a long period of time. The output power is plotted versus time and the plot of the first measurement can be seen in Figure 7.1.



Hot and cold vs time measurement: 19-06-2015

Figure 7.1: The first measurement of the stability of the hot and cold load. The total time of the measurement was 6000 s. A polynomial has been fitted of order 10 and has been subtracted from the data to show the residuals.

We see in Figure 7.1 that the overall fluctuations are at maximum 0.00001 mW of the total output power and the more frequent fluctuations are due to the random noise in the electrical components, with the highest contribution coming from the power meter. These fluctuations are calculated using a fit, this fit is subtracted from the data and the root mean square is determined. These residuals show the stability of the system. The overall error of the first measurement of the cold load is 0.068%. The hot load shows an increase in power after around 3000 s. This is probably due to the temperature changes in the atmosphere during the measurement.

In Figure 7.1 we can see that the cold load definitely has a sinusoidal function that it follows after the first  $\sim 1000$  s. We see that around the sinusoidal there are small fluctuations. These fluctuations are again due to the noise fluctuations of the output meter. The cold load also displays some unexpected behaviour, it does not follow the same shape as the hot load. At first the output power of the cold load increases up to about 1000 s. This behaviour is not understood and to see if this was only a one time phenomenon, the measurement was taken again.

The second measurement of the hot and cold load is shown in Figure 7.2.



Hot and cold vs time measurement: 26-06-2015

Figure 7.2: The second measurement of the stability of the hot and cold load. The total time of the measurement was 4200 s. A polynomial has been fitted of order 10 and has been subtracted from the data to show the residuals.

We can see there is a strong difference between Figure 7.1 and 7.2. The second measurement receives more power, hence we measure a different receiver temperature. This already shows that it is important to measure the hot and cold load at each sky measurement to measure the receiver temperature. The top plot in Figure 7.2 shows that the output power is changing after the first  $\sim 1200$  s. This could be due to the high room temperature causing a rapid evaporation of the liquid nitrogen, however, on the middle plot of Figure 7.2 we see that the output power of the hot load is also changing after  $\sim 1500$  seconds. This gives some indication that the atmospheric temperature is decreasing.



Hot and cold vs time measurement: 29-06-2015

Figure 7.3: The third measurement of the stability of the hot and cold load. The total time of the measurement was 12350 seconds. A polynomial has been fitted of order 10 and has been subtracted from the data to show residuals.

Since there are big differences in the shapes of Figures 7.1 and 7.2 another measurement was taken. The third measurement is shown in Figure 7.3. This measurement was taken for a longer period of time. We can see that the shape of the hot and cold load are similar to that of Figure 7.2. However, when looking closer at the axis, it shows that the output power of the hot and cold load decreases at different times. Again, the overall changes in the output powers are probably due to the changes in atmospheric temperature, thereby explaining the difference in decreasing output power at different times.

### 7.2. Receiver Temperature of the Telescope

The receiver temperature of the telescope is calculated via the hot and cold load output powers. The receiver temperature is plotted for all three measurements, of these measurements the average temperature is determined along with the scatter around the mean of all the points. The results of the hot and cold measurements can be seen in Figure 7.4 and the average output powers with the average receiver temperature are shown in Table 7.1.

Measurement	$P_{hot,aver}$ (dBm)	$P_{cold,aver}$ (dBm)	$T_{RX,aver}(K)$
1	$-20.93 \pm 0.02$	$-23.39 \pm 0.02$	$207.98 \pm 0.64$
2	$-20.83 \pm 0.02$	$-23.25 \pm 0.02$	$215.72 \pm 0.71$
3	$-20.92\pm0.02$	$-23.41 \pm 0.02$	$204.35 \pm 0.63$

Table 7.1: Experimental results of receiver temperature.'P<sub>hot</sub> (dBm)' is the output power at atmospheric temperature and 'P<sub>cold</sub> (dBm)' at liquid nitrogen temperature of 77.15 K.  $T_{RX}(K)$  is the receiver temperature.

From Figure 7.4 we can see that the overall receiver temperature of all the measurements vary within a few Kelvin. The difference between the maximum and minimum receiver temperature of the measurements are shown in Table 7.2, along with the mean value of the receiver temperature and the standard deviation.

Measurement	$\mathbf{Difference}(\mathbf{K})$	Mean(K)	$\sigma_T(\mathbf{K})$
1	3.47	207.98	0.641
2	4.95	215.72	0.714
3	3.84	204.35	0.632

Table 7.2: The difference between the maximum and minimum, the mean and the standard deviation of the receiver temperature.

The receiver temperatures are higher than expected. This is due to a relative high atmospheric temperature and due to an error in the cold load that is addressed in Section 7.3. For the first measurement an atmospheric temperature of 293 K is assumed due to loss of data. For the second and third measurement an atmospheric temperature of 295 K was measured.

Several data points from the third measurement were corrupted and for that reason the data set was reduced to a smaller data set. The corrupted data points were probably an error in the read-out and so those data points could not be used as actual measurements.

In order to calculate the error in the receiver temperature, a fit was applied to the data points. This fit was then subtracted from the data points and the root mean square was calculated for these values. The plot with the residuals of the receiver temperatures can be seen in Figure 7.5.



Figure 7.4: Using the hot and cold output powers, the receiver temperature is calculated for all three measurements and plotted as a function of time. A polynomial has been fitted of order 10 and has been subtracted from the data to show the residuals, which are shown in Figure 7.5.



**Residuals of Receiver Temperature** 

Figure 7.5: The residuals after the fit has been subtracted from the data.

#### 7.3. Error in Receiver Temperature

Following the first couple of measurements of the receiver temperature and the system temperature (for the measurements of the system temperature see Mulder (2015)), it was concluded that there had to be an error in the receiver temperature. The reason for this was a higher receiver temperature than system temperature, which is not possible.

The cold load has a higher temperature than we assumed. We assumed that the beam of the horn looked at a temperature of 77 K. This is however not the case, it looks at a higher temperature, due to the construction and position of the mirror for the cold load, the beam was not filling the entire cold load.

To test by how much the temperature of the cold load is higher, we took the horn from the frame. We then pointed the horn directly in the hot and cold load, this method allowed us to be sure that the beam was completely filled by the hot and cold load. The output power of these measurements were read out by the power meter and from the data a receiver temperature was calculated. The results are shown in Table 7.3.

Measurement	$P_{hot,aver}$ (dBm)	$P_{cold,aver}$ (dBm)	$T_{RX,aver}(K)$	$T_{hot,aver}(\mathbf{K})$
1 (01-07-2015)	$-20.88 \pm 0.02$	$-23.46 \pm 0.02$	$195.33 \pm 3.05$	297
2(06-07-2015)	$-20.99 \pm 0.02$	$-23.49 \pm 0.02$	$205.77 \pm 1.98$	298
3(06-07-2015)	$-20.98 \pm 0.02$	$-23.49 \pm 0.02$	$204.99 \pm 2.10$	297.56
4(06-07-2015)	$-20.97\pm0.02$	$-23.49 \pm 0.02$	$203.88 \pm 3.03$	297.69

Table 7.3: Measurements of the receiver temperature done by hand.

Then we placed the horn back on the frame and took again the measurements of the hot and cold load. This will result in a different receiver temperature than previously measured. The results of the measurements are shown in Table 7.4.

Measurement	$P_{hot,aver}$ (dBm)	$P_{cold,aver}$ (dBm)	$T_{RX,aver}(K)$	$T_{hot,aver}(\mathbf{K})$
1 (01-07-2015)	$-20.91 \pm 0.02$	$-23.33 \pm 0.02$	$219.20 \pm 0.33$	297
2(06-07-2015)	$-20.97\pm0.02$	$-23.34 \pm 0.02$	$226.94 \pm 0.54$	298
3(06-07-2015)	$-20.97\pm0.02$	$-23.34 \pm 0.02$	$227.51 \pm 0.44$	297.56
4 (06-07-2015)	$-20.97\pm0.02$	$-23.34 \pm 0.02$	$227.88 \pm 0.41$	297.69

Table 7.4: Measurements of the receiver temperature done with the complete the system.

From here we can indeed see a relative large difference between the receiver temperatures, for these measurements a hot load temperature of 298 K is used. By using the receiver temperatures of the measurements in Table 7.3 and the Y-factor of Table 7.4, we can calculate what cold load temperature the system is actually seeing instead of the 77 K. This calculation is just rewriting equation 13 for  $T_{\rm cold}$ . The results can be seen in Table 7.5.

Measurement	$T_{\rm cold, \ corr}({\rm K})$
1(01-07-2015)	87.57
2(06-07-2015)	85.90
3(06-07-2015)	86.46
4(06-07-2015)	87.08
Average	86.75

Table 7.5: Corrections of the temperature for the cold load.

Using these value for the cold load, the receiver temperature is recalculated and the results are shown in table 7.6.

Measurement	$T_{RX,aver}(K)$
1(01-07-2015)	$196.60 \pm 0.31$
2(06-07-2015)	$206.16\pm0.65$
3(06-07-2015)	$204.99 \pm 0.50$
4(06-07-2015)	$203.88 \pm 0.50$

Table 7.6: Correct receiver temperature calculated using adjusted  $T_{\rm cold}$ .

Taking field measurements over the course of a couple of days revealed a new problem regarding the cold load. It turned out the cold load is not as reliable as we thought. The measurements in the field showed variations in output power for the cold load of  $\sim 1 \cdot 10^{-4}$ mW over the course of several days, see Mulder (2015). These variations are large enough to cause a wrong temperature of the cold load for field measurements. These differences are from the fact that the beam of the horn is probably not filling the entire cold load. Another explanation is that reflections from the beam is causing for the effect that the horn is seeing itself, this is likely to happen, since observing the cold load at an angle shows a different output power. In the lab this has likely happened as well, but the measurements were always taken at the same place, resulting in the same contribution of excess output power for all the measurements and therefore a correct temperature of the cold load.

Due to the deadline of the thesis, this problem could not be directly solved. A temporary solution is described in Mulder (2015).

## 8. Improvements

There are improvements to be made regarding the back-end and frame of the telescope, especially the frame itself.

The back-end of the telescope can be improved by using completely new components, like the amplifiers and filters. As of now, we are using two different kind of amplifiers of which one amplifier we do not have any specifications, on for example the 1-dB compression point of the . Using new amplifiers allows us have a lower receiver temperature. Improvements can also be made on connecting the components via the SMA cables. Using the same type of cables and having them as short as possible will reduce the loss of the signal and the overall noise of the receiver.

The error in the receiver temperature as a result of the beam missing some of the cold load can be avoided by making sure the complete beam is hitting the cold load. This would require some adjustments to the frame to allow for a larger mirror and a larger cold load. Making a new frame for the telescope where the main frame and under frame are constructed as one piece will allow for a frame which is better suited for a larger cold load. With more time to make adjustments, a ellipsoidal mirror instead of a flat mirror would also improve the functionality of the cold load, since a ellipsoidal mirror allows us to focus the beam at the cold load. Thereby ensuring a beam that is completely filled by the cold load.

A future upgrade would be to make a interferometer and to have it rotate horizontally in order to make a full sky measurement.

# 9. Conclusion

As part of a radio telescope to measure the CMB, a receiver and a frame had to be designed and constructed. The frame had to be build to function as support for the receiver, horn, hot load, cold load and equipment. The receiver was constructed from two amplifiers and a band pass filter with a bandwidth of 1.05 GHz. The back-end noise temperature is around 130 K (see Table 4.3). The frame consists of two parts, the main part that houses the back-end and the horn and the under frame which is for the equipment needed to operate the telescope and store data.

Some unforeseen adjustments had to be made to allow us to complete the telescope, but the telescope itself works and for the results of the measurements see Mulder (2015) and Sweijen (2015). However, the telescope definitely needs to be adjusted to be used in the course Radio Astronomy. The cold load caused an error in the calibration, for this a temporary solution is used, see Mulder (2015).

# 10. Acknowledgments

First of all I would like to thank the supervisors Prof. Dr. Andrey Baryshev, Dr. Ronald Hesper and Dr. John P. Mckean for the opportunity of creating a telescope and their help with it. It was a great and sometimes annoying experience to encounter all sorts of problems during designing, discussing and constructing the telescope.

Second, I would like to thank the people of SRON. In particular Bert Kramer, Rob van der Schuur, Andrey Khudchenko and Duc van Nguyen for their help in construction and supplying parts needed to create the telescope. I would like to thank Jan Barkhof for his help on the Allan Variance. Without their help it was not possible to complete this part of the telescope.

Finally, I would like to thank my fellow students Bram Lap, Willeke Mulder and Frits Sweijen. It was a great experience with the four of us and without each others help, this project would have been far from complete.

# 11. References

Technologies Agilent. Agilent Fundamentals of RF and Microwave Noise Figure Measurements, 2010.

Technologies Agilent. Agilent E4418B Power Meter, eighth edition, April 2013.

- D.W. Allan. Statistics of atomic frequency standards. *IEEE Proceedings*, 54:221–230, February 1966. doi: 10.1109/PROC.1966.4634.
- J. Barkhof. ALMA Band 5 Cartridge Output Power Stability Test Procedure . page 11, April 2015.
- J.P. Bentley. *Principles of Measurement Systems*. Pearson Education, fourth edition, 2005.
- B. Boashash. Estimating and Interpreting The Instantaneous Frequency of a Signal-Part 1: Fundamentals. *Proceedings of the IEEE*, 80(4), April 1992.
- L. Dickstein. Introduction to Phase Noise in Signal Generators. Giga-tronics, 2012.
- D. J. Fixsen. The Temperature of the Cosmic Microwave Background. Astrophysical Journal, 707:916–920, December 2009.
- L. Frenzel. What's The Difference Between The Third-Order Intercept And The 1-dB Compression Points? *Electronic Design*, October 2013.
- B.N.R. Lap. Design of a Pickett-Potter Horn to measure the CMB at 11 GHz, July 2015.
- R. Mancini. Op Amps For Everyone. Texas Instruments, second edition, August 2002.
- W. Mulder. Calibration of a 11GHz Pickett-Potter Horn and measurements of the Cosmic Microwave Background, July 2015.
- H.H. Pickett, J.C. Hardy, and J. Farhoomand. Characterization of a Dual-Mode Horn for Submillimeter Wavelengths. *IEEE Transactions on Microwave Theory and Techniques*, MTT-32(8):936–937, August 1984.
- P.D. Potter. A New Horn Antenna with Suppressed Sidelobes and Equal Beamwidths. Microwave J., (6), February 1963.
- SIM. Characterization of frequency and phase noise. International Radio Consultative Committee, pages 142–150, 1986. Reprinted, SIM: Society of Instrumentation and Measurement.
- F. Sweijen. Computer Control of a Horn Antenna and Measuring the Sun at 11 GHz, July 2015.
- T.L. Wilson, K. Rohlfs, and S. Hüttemeister. *Tools of Radio Astronomy*. Springer, sixth edition, June 2013.

# A. Allan Variance Script

```
#!/usr/bin/env python
from __future__ import division
import numpy as np
import matplotlib
from matplotlib.pyplot import figure, show, rc
#Reading in the data set
x, y = np.loadtxt('Data500.txt', usecols = (0,1), unpack=True)
x1, y1 = np.loadtxt('Data1000.txt', usecols=(0,1), unpack=True)
x2, y2 = np.loadtxt('Data3000.txt', usecols=(0,1), unpack=True)
x3, y3 = np.loadtxt('Data6000.txt', usecols=(0,1), unpack=True)
x4, y4 = np.loadtxt('hotcold_19062015.txt', usecols = (1,3), unpack=True)
day = 1
def Allanvariance(data,tau_0):
  Defining input variables
  tau_0: Minimum sample time of data set
  data: 1D array of the output values
    Defining program parameters
    N: Length of the complete data set
    Average: the average value of the complete data set
    M: Number of samples
    n\colon size of the samples, where n is an integer
  , , ,
    # Setting inital parameters
  N = len(data)
  average = np.mean(data)
  lengthoutput = 0
  Alvar = []
  tau = []
  time = []
  k = 1
  while k < N/3:
      Determining the size of the output array; output array has to be small
    enough
             in order to calculate the last Allan variance.
             Corresponding to the lenght output, the program calculates the time
     array in
             timesteps of tau_0.
       . . .
      k += 1
      lengthoutput += 1
      time.append(tau_0 * k)
  for q in time:
        #Looping through the time array to get multiply values for n e.g. the
    size of the sample.
    n = int(q/tau_0)
    \mathbf{k} = \mathbf{0}
```

```
M = 1
    alvar = 0
    while k < lengthoutput:
            \# For each n calculate the allan variance.
      i = int(k*n)
      ip = int((k+1)*n)
      j = int((k+1)*n)
      jp = int((k+2)*n)
      if jp > N:
        break
      else:
        p_{-i} = np.mean(data[i:ip+1:])
        p_j = np.mean(data[j:jp+1:])
        av = ((p_i) - (p_j)) **2 / average **2
        M += 1
      alvar += 0.5 * av/M
      k += 1
    Alvar.append(alvar)
  return Alvar, time
alvar, t = Allanvariance(y, 0.05)
alvar1, t1 = Allanvariance(y1, 0.05)
alvar2, t2 = Allanvariance(y2, 0.05)
alvar3, t3 = Allanvariance(y3, 0.05)
alvar4, t4 = Allanvariance(y4, 11.85)
\# Plotting code
fig = figure()
fig.suptitle('Allan variance: lab measurement 0%s-07-2015' %day, fontweight='
   bold', fontsize=16)
frame = fig.add_subplot(2,2,1)
frame.set_xscale('log')
frame.set_yscale('log')
frame.set_xlabel('Time (s)')
frame.set_ylabel('$\sigma^2 (\\tau)$')
frame.plot(t, alvar, label='500s')
frame.legend()
frame.grid()
frame1 = fig.add_subplot(2,2,2)
frame1.set_xscale('log')
frame1.set_yscale(', log')
frame1.set_xlabel('Time'(s)')
frame1.set_ylabel('$\sigma^2 (\\tau)$')
frame1.plot(t1,alvar1,label='1000s')
frame1.legend()
frame1.grid()
frame2 = fig.add_subplot(2,2,3)
frame2.set_xscale('log')
frame2.set_yscale('log')
```

```
frame2.set_xlabel('Time (s)')
frame2.set_ylabel('$\sigma^2 (\\tau)$')
frame2.plot(t2,alvar2,label='3000s')
frame2.legend()
frame3 = fig.add_subplot(2,2,4)
frame3.set_xscale('log')
frame3.set_yscale('log')
frame3.set_ylabel('Time (s)')
frame3.set_ylabel('$\sigma^2 (\\tau)$')
frame3.plot(t3,alvar3,label='6000s')
frame3.legend()
fig.savefig("Allanvarariance_0%s_05_2015.png" %day)
show()
```

# B. List of Parts

Bolts			Nuts	Washers
Size	Length	Amount	Amount	Amount
M2.5	6  mm	2	2	2
M2.5	$16 \mathrm{mm}$	4	4	4
M3	$5 \mathrm{mm}$	2		
M3	$8 \mathrm{mm}$	4	2	2
M3	$12 \mathrm{mm}$	2		2
M3	$25 \mathrm{~mm}$	2		2
M3	$30 \mathrm{~mm}$	2	2	4
M4	$30 \mathrm{~mm}$	4	4	4
M5	$15 \mathrm{~mm}$	4	4	4
M6	$20 \mathrm{~mm}$	4		
M6	$40 \mathrm{mm}$	8		
Other				·
8 rings				
12 Rivet nuts				

Table B.1: A complete list of all parts used to mounted the frame, motor and horn together.

# C. The Script for Data Reduction

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

```
from __future__ import division
from matplotlib import pyplot
from matplotlib.pyplot import figure, show
import numpy as np
import time
#_____ Date: 29-06-2015 =____
T_cold = 77 \# K
T_{hot19} = 273.15 + 20 \# K
T_{hot26} = 273.15 + 22 \#K
T_{hot29} = 273.15 + 22 \#K
erT_hot = 0.001 \ \#K
erT_cold = 1 \#K
erhot = 0.02
ercold = 0.02
# Reading in data file
time_cold19, power_cold19, time_hot19, power_hot19 = np.loadtxt('
    hotcold_19062015.txt', usecols = (0, 1, 2, 3), unpack=True)
time_cold26, power_cold26, time_hot26, power_hot26 = np.loadtxt(')
    data140626-hotcold.txt', usecols = (0, 1, 2, 3), unpack=True)
time_cold29, power_cold29, time_hot29, power_hot29 = np.loadtxt('
    data140629_hotcold20.txt', usecols = (0,1,2,3), unpack=True)
#Removing corrupt data
time_cold29 = time_cold29[87:472:]
power_cold29 = power_cold29 [87:472:]
time_{hot29} = time_{hot29} [87:472:]
power_hot29 = power_hot29[87:472:]
# Converting time in data file to real time of the measurement.
def Timeconvert(dataarray):
  Time = []
  j = 0
  while j < len(dataarray):
    time \ = \ dataarray \left[ \ j \ \right] \ - \ dataarray \left[ \ 0 \ \right]
    Time.append(time)
    j += 1
  return Time
# Definition for the Y-factor as calucated in (Zandvliet (2015)).
def Yfactor(hot, cold):
  Y = 10 * * ((hot - cold) / 10)
  return Y
\# Definition for the effective noise temperature as calucated in (Zandvliet
    (2015)).
def Tempeff(Y, T_hot, T_cold):
```

```
T_{eff} = (T_{hot} - T_{cold} * Y) / (Y-1)
```

```
return T_eff
```

```
# Error calculations in the Y-factor and effective noise temperature.
def ErrorY(Y):
  \operatorname{errordifP} = (\operatorname{ercold} **2 + \operatorname{erhot} **2) **0.5
  error_Y = ((Y * 1/10 * np.log(10) * errordifP) * * 2) * * 0.5
  return error_Y
def ErrorT_eff(Y,T_hot,T_cold):
  errhot = (1/(Y-1)) **2 * erT_hot **2
  errcold = (-Y/(Y-1)) **2 * erT_cold **2
  errY = (((T_cold - T_hot) / (Y-1)**2)**2) * (ErrorY(Y))**2
  \operatorname{err} T_{-}\operatorname{eff} = (\operatorname{errhot} + \operatorname{errcold} + \operatorname{err} Y) * * 0.5
  return errT_eff
# Converting dBm to mW
def mWconvert(data):
  return 10 * * (data/10)
# Fitting polygon to effective temperature
def Fit(Time, power, order):
  coefficients = np. polyfit (Time, power, order)
  polynomial = np.poly1d(coefficients)
  newx = np.linspace(0, max(Time), len(Time))
  newy = polynomial(newx)
  return newx, newy
# Calcuting standard deviation from the fitted polygon
def stdev(datanew, power):
  New = []
  for k in xrange(0,len(datanew)):
    New. append (datanew [k] - power [k])
  percentage = np.std(New) / np.mean(power) * 100
  return New, percentage
# Calculating average sample time between measurements
def Samplet(Time):
  Aver_t = 0
  for l in xrange (0, \text{len}(\text{Time}) - 1):
     Aver_t += Time[l+1] - Time[l]
    sampletime = Aver_t/len(Time)
  return sampletime
# Printing out the values.
def Average(power1, power2, temp, unc):
  # Setting intitals for averaging
  temperature = 0
  err = 0
  hl =0
  c1 = 0
  for i in xrange(0,len(power1)):
    # Calculating Averages
    cl += power1[i]
    aver1 = cl/len(power1)
    hl += power2[i]
    aver2 = hl/len(power2)
```

```
temperature += temp[i]
err += unc[i]**2
avererr = 1/((len(power1))**0.5) * (err)**0.5
aver = temperature/len(power1)
return aver1, aver2, aver
```

```
# Calculates all the values and plots the values
def Calculations (time_coldsys, Power_coldsys, time_hotsys, Power_hotsys, T_hot,
   order, Datum):
  #Calculations for the system
  Ysys = Yfactor (Power_hotsys, Power_coldsys)
  Tsys = Tempeff(Ysys, T_hot, T_cold)
  UncYsys = ErrorY(Ysys)
  UncTsys = ErrorT_eff(Ysys, T_hot, T_cold)
  averclsys, averhlsys, aversys = Average(Power_coldsys, Power_hotsys, Tsys,
    UncTsvs)
  Power_coldsys = mWconvert(Power_coldsys)
  Power_hotsys = mWconvert(Power_hotsys)
  time_coldsys = Timeconvert(time_coldsys)
  time_hotsys = Timeconvert(time_hotsys)
  hxsys , hysys = Fit (time_hotsys , Power_hotsys , order )
  cxsys , cysys = Fit(time_coldsys, Power_coldsys, order)
  Txsys , Tysys = Fit(time_coldsys, Tsys, order)
  New_hotsys , percentage_hotsys = stdev(hysys ,Power_hotsys)
  New_coldsys , percentage_coldsys = stdev(cysys , Power_coldsys)
  New_tempsys , percentage_tempsys = stdev(Tysys, Tsys)
  avertsys = Samplet(time_coldsys)
  # Prints results for the system measurements
  --- "%Datum
  print "_____
                             -Measurement by system------
  print "Average P_hot (dBm): ".ljust(50)+ "%.4f + %.4f"%(averhlsys, erhot)
        'Average P_cold (dBm):".ljust(50)+ "%.4f + %.4f"%(averclsys , ercold)
  print '
  print "Average T_eff (K):".ljust(50)+ "\%.4f + \%.4f"%( aversys , np.std(
   New_tempsys))
  print "Y-factor".ljust (50)+ "%.2f + %.4f"%(np.mean(Ysys), np.mean(UncYsys))
  print "----
  print "The RMS of the hot load is ".ljust(50)+ "%.3e mW' %np.std(New_hotsys)
  print "The error in the hot load is ".ljust(50)+ "%.3f %%" %percentage_hotsys
  print "-----
  print "The RMS of the cold load is ".ljust(50)+ "%.3e mW" %np.std(New_coldsys
    print "The error in the cold load is ".ljust(50)+ "%.3f %%" %
   percentage_coldsys
  print "-
  print "The RMS of the receiver temperature is ".ljust(50)+ "%.3f K" %np.std(
   New_tempsvs)
  print "The error in the receiver temperature is ".ljust(50)+ "%.3f %" %
   percentage_tempsys
  print "-
```

```
print "The average sample time is ".ljust(50)+ "%.2f s" %avertsys
print ""
#Plotting code
#Plots hot and cold load versus time
fig = figure(num=None, figsize=(10.5, 10.5), dpi=100, facecolor='w',
 edgecolor='k')
fig.suptitle('Hot and cold vs time measurement: %s-06-2015' %Datum,
 fontweight='bold', fontsize=16)
fig.subplots_adjust(hspace=.6)
frame = fig.add_subplot(4,1,1)
frame.set_title('P$_{cold}$ vs time')
frame.set_xlabel('Time (s)')
frame.set_ylabel('P_{cold} [mW]')
frame.plot(time_coldsys, Power_coldsys, label="Data")
frame.plot(cxsys, cysys, 'r', label="Fit")
frame.legend()
frame.grid()
frame = fig.add_subplot(4,1,2)
frame.set_title('Residuals of P$_{cold}$ vs time')
frame.set_xlabel('Time (s)')
frame.set_ylabel('P_{cold} $ [mW]')
frame.plot(time_coldsys, New_coldsys, label="Data")
frame.legend()
frame.grid()
frame1 = fig.add_subplot(4,1,3)
frame1.set_title('P$_{hot}$ vs time')
frame1.set_xlabel('Time (s)')
frame1.set_ylabel('P { hot } [mW]')
frame1.plot(time_hotsys, Power_hotsys, label="Data")
frame1.plot(hxsys, hysys, 'r', label="Fit")
frame1.legend()
frame1.grid()
frame1 = fig.add_subplot(4,1,4)
frame1.set_title('Residuals of P$_{hot}$ vs time')
frame1.set_xlabel('Time (s)')
frame1.set_ylabel('P\$_{hot} [mW] ')
frame1.plot(time_hotsys, New_hotsys, label="Data")
frame1.legend()
frame1.grid()
#Shows residuals
fig = figure(num=None, figsize=(10.5, 8.5), dpi=100, facecolor='w', edgecolor
 ='k'
fig.suptitle('The Data with Subtracted Fit: %s-06-2015 ' %(Datum), fontweight
 ='bold', fontsize=16)
fig.subplots_adjust(hspace=.6)
frame = fig.add_subplot(3,1,1)
frame.set_title('P$_{cold}$ vs time')
```

```
frame.set_xlabel('Time (s)')
```

```
frame.set_ylabel('P_{s} \{ cold \}  [mW]')
frame.plot(time_coldsys, New_coldsys, label="Data")
frame.legend()
frame.grid()
frame1 = fig.add_subplot(3,1,2)
frame1.set_title('P$_{hot}$ vs time')
frame1.set_xlabel('Time (s)')
frame1.set_ylabel('P { hot } [mW]')
frame1.plot(time_hotsys, New_hotsys, label="Data")
frame1.legend()
frame1.grid()
frame2 = fig.add_subplot(3,1,3)
frame2.set_title('T$_{RX}$ vs time')
frame2.set_xlabel('Time (s)')
frame2.set_ylabel('T(K)')
frame2.plot(time_coldsys, New_tempsys, label="Data")
frame2.legend()
frame2.grid()
fig.savefig("AColdhotstability_res_%s-06.png" %(Datum))
#Plots receiver temperatures
fig = figure(num=None, figsize=(10.5, 8.5), dpi=100, facecolor='w', edgecolor
 ='k'
fig.suptitle('Receiver Temperatures', fontweight='bold', fontsize=16)
fig.subplots_adjust(hspace=.6)
frame = fig.add_subplot(1,1,1)
frame.set_title("Measurement System : %s-06-2015" %(Datum))
frame.set_xlabel('Time (s)')
frame.set_ylabel('T(K)')
frame.plot(time_coldsys, Tsys, label="Data")
frame.plot(Txsys, Tysys, 'r', label="Fit")
frame.legend()
frame.grid()
fig.savefig("Receivertemps_0%s-06.png" %(Datum))
#Plots receiver temperatures with subtracted fit
fig = figure(num=None, figsize=(10.5, 8.5), dpi=100, facecolor='w', edgecolor
 = 'k ')
fig.suptitle('Receiver Temperatures Subtracted Fit', fontweight='bold',
 fontsize = 16)
fig.subplots_adjust(hspace=.6)
frame = fig.add_subplot(1,1,1)
frame.set_title('Date: \%s - 06 - 2015' %(Datum))
frame.set_xlabel('Time (s)')
frame.set_ylabel('T(K)')
frame.plot(Txsys, New_tempsys)
frame.grid()
fig.savefig("AColdhotstability_varT_0%s-06.png" %(Datum))
```

show()
return

### # Calculating the values.

<sup>#</sup> Calculations (time\_cold19, power\_cold19, time\_hot19, power\_hot19, T\_hot19, 10, 19) Calculations (time\_cold26, power\_cold26, time\_hot26, power\_hot26, T\_hot26, 10, 26) Calculations (time\_cold29, power\_cold29, time\_hot29, power\_hot29, T\_hot29, 10, 29)