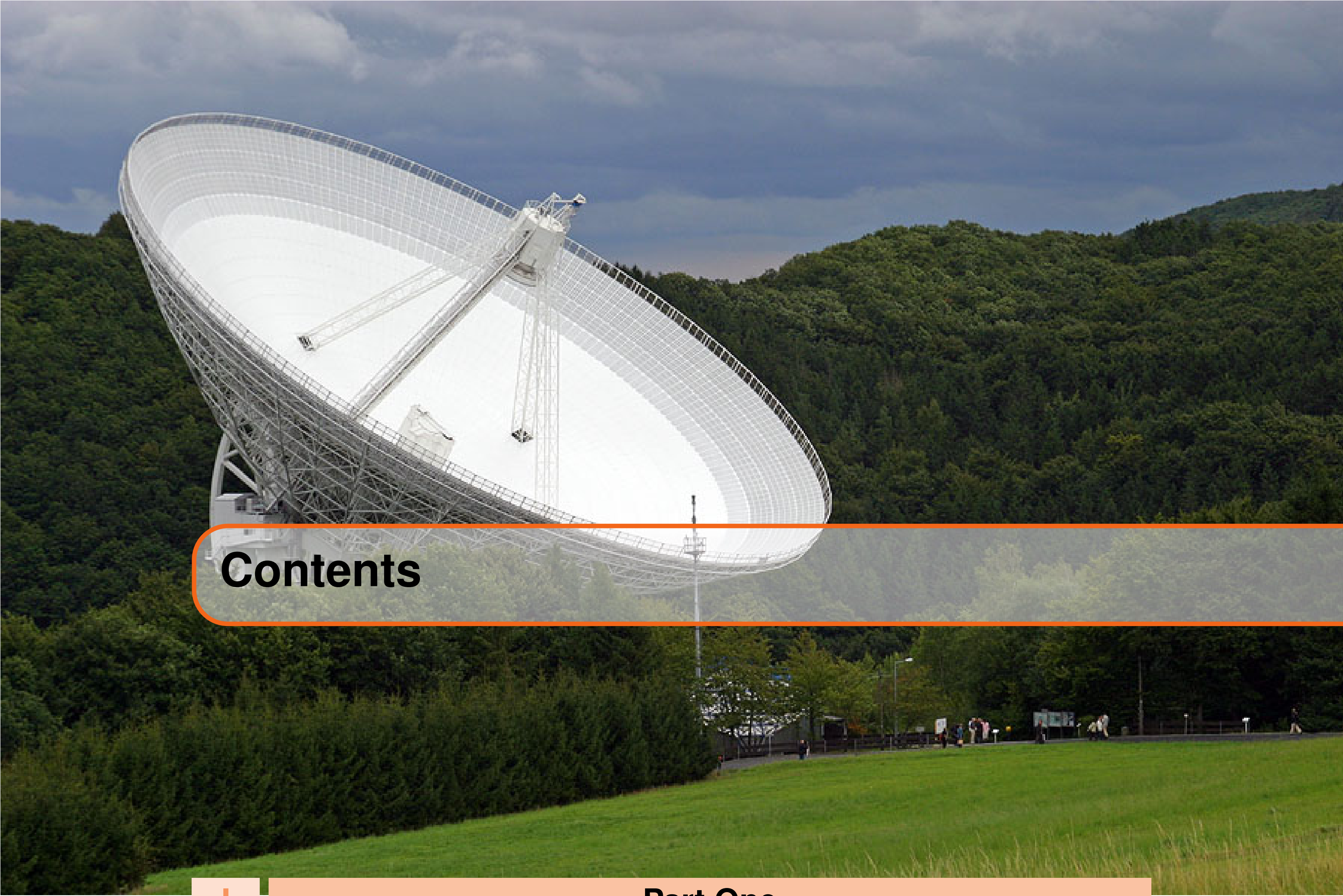
Radio Astronomy Lab

The Argelander-Institut für Astronomie (AIfA)



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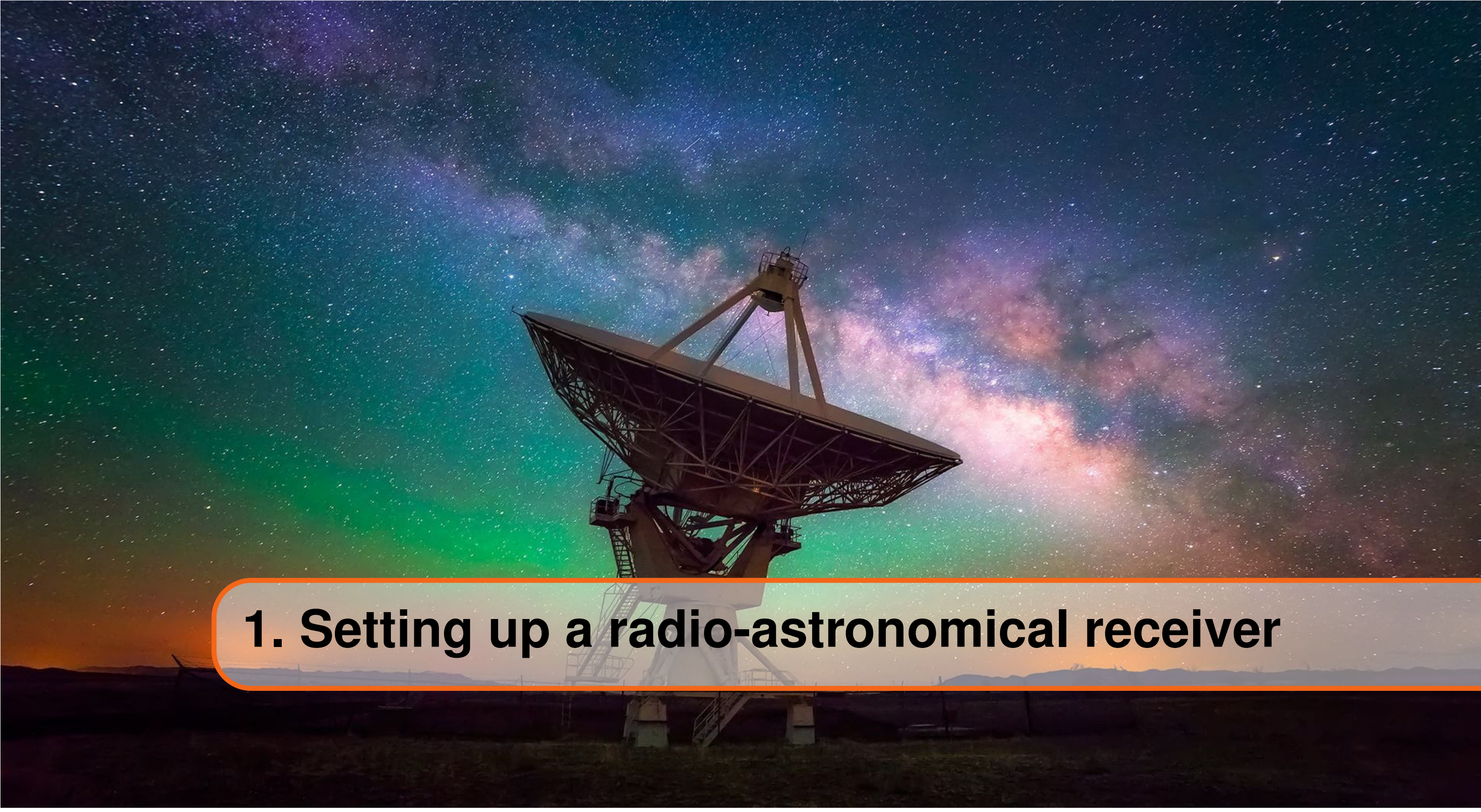

1. Setting up a radio-astronomical receiver

1.1 Preliminary remark

The preparation and execution of this radio lab give students a basic understanding of the most important terms and parameters of a Heterodyne receiver. In principle, the experimental setup has all essential components of a heterodyne receiver system, such as amplifiers, mixers, and filters. This receiver system is used in Earth observation, atmospheric exploration, plasma diagnostics, and radio astronomy. Therefore, this lab is closely related to projects at our institute and should arouse the interest for future works in one of our research groups. It is important to note that the previous setup had been in operation for a long time. Over the years, high-frequency (HF) electronic components had degraded to the extent that it was challenging to obtain accurate measurements. A team of four Ph.D. students and two master students have upgraded the hardware and changed some parts to make the lab scientifically and didactically more attractive and reliable.

1.2 Notes on writing your lab report

Terms printed in **bold** should be **explained**, and formulas marked with asterisk ($*$) should be derived in your report.

1.3 Introduction

In radio astronomy, electromagnetic waves are collected by a radio telescope and converted into an **electrical signal**. These signals are so weak that they are not directly detectable. Therefore, a huge amplification is necessary – amplification factors of the order of 10^{10} (100 dB) are common. The amplification is done by a receiver, in general a superheterodyne receiver. The receiver performance is of paramount importance as it needs to amplify a weak input signal without adding too much noise and avoiding feedback. The current experiment makes the student familiar with active and passive components of a receiver. A working receiver is set up, utilizing the heterodyne technique, with **down-conversion** of the high-frequency signal to an **intermediate frequency (IF)**. A comprehensive treatment of the heterodyne principle can be found in Chapter 6 of the lecture notes to “Radio Astronomy: Tools, Applications, and Impacts” (course astro 841).

The detection of the signal is done in a **backend**. Detection means the transformation of an alternating signals into a form that is useful for the scientific purpose. In case of continuum observations the backend must provide a total- power signal over some **bandwidth**, along with the polarization parameters. In spectroscopy the task is to analyze the frequency dependence of the signal with high **spectral resolution**, while a high time resolution is required in case of (e.g.) pulsar observations. For this experiment, we use a backend delivering a signal that is proportional to the total power at the input. In addition, we use a spectrum analyzer to study the frequency dependence of an astronomical receiver.

1.4 Contents and Goals of the Experiment

In this experiment, you will study the amplification of a radio signal. The amplification usually cannot be performed in one step, but makes use of the so-called superheterodyne method. This is the stepwise amplification of the signal at two or more different frequencies[1], where the original signal is downconverted to a lower frequency using a mixer.

Definition 1.4.1 — Superheterodyne receiver. A superheterodyne receiver is a type of radio receiver that converts a received radio signal to a fixed intermediate frequency (IF) using a frequency mixer. IF signals can be processed more conveniently than the original ones.

This technique is necessary to facilitate amplifications of the order 10^{10} or 100 dB, for several technical reasons. First of all, it is not easy to transmit a high-frequency (HF) signal through a conductor over some distance without having significant losses. Furthermore, there is inevitably feedback from subsequent parts of the receiver chain, making the receiver system instable. Heterodyne amplification is hence indispensable to avoid feedback. In addition, superheterodyne receivers allow the backends to be used at the same frequency for all observing frequencies, as the system always works at the same IF. And finally, the heterodyne principle allows to tune the observing frequency in case of spectral line measurements, while keeping the IF fixed.

In this experiment a superheterodyne receiver will be set up. In the first step, the single components will be examined in detail. Some essential characteristics of the components will be measured. Finally, the whole receiver will be calibrated using the **hot-cold** calibration. The emitted power of an absorber, first kept at room temperature and then cooled with liquid nitrogen ($\sim$ 77K) defines a linear relation between temperature and voltage measured with the backend. This linear relation allows to determine the **receiver temperature**. The calibrated receiver can now be used to determine the noise temperature of a noise diode. Furthermore, the influence of the atmosphere on an astronomical observation will be simulated. Finally, you will get a short introduction to spectroscopy.

The goal of this experiment is to give you insights to individual electronic components used in radio-astronomy and the mode of operation of a superheterodyne receiver.

1.5 Characteristics of Individual Receiver Components

Each receiver component is characterized by a **gain** G. Passive components have $G < 1$. The total amplification of a receiver is the product of the individual gains (or the sum of the gains, if they are given in dB)

[1] In most cases only two frequencies are used: the radio frequency (RF) is the original frequency of the astronomical signal that is transformed to the intermediate-frequency (IF).

$$G_{\text{rec}} = \prod_{i=1}^{n} G_{\text{i}} \tag{1.1}$$

$$G_{\text{rec}}[dB] = \sum_{i=1}^{n} G_{\text{i}}[dB] \tag{1.2}$$

The second important parameter of a receiver is its **noise temperature**. This is the noise temperature that would be measured if the receiver had no input signal, i.e. having a matched resistor at $T = 0$ K as input. In practice, the receiver noise temperature is the most important parameter as it defines the detection limit.

It is possible to define a noise temperature for every single component. The noise temperature of a component is defined as the physical temperature of a hypothetical resistor at the input of an assumed noiseless device that would produce the same measured output noise. This noise temperature can be easily calculated for passive components like resistors, but it is in most cases impossible to calculate the noise temperature of an active component. The receiver temperature can be calculated from the individual noise temperatures via

$$T_{\text{rec}} = T_1 + \sum_{i=2}^{n} \frac{T_{\text{i}}}{\prod_{k=1}^{i-1} G_{\text{k}}[W]}. \tag{1.3}$$

Obviously, the first component is most important, as the subsequent contributions become progressively smaller. The receiver noise temperature and therefore the detectability of faint sources is dominated by the first few components of a receiver. Further amplification or attenuation before the backend does not change the detectability of radio sources any more. The total amplification of a receiver is therefore not a relevant parameter (it is only required to provide sufficient power to the detector unit, or backend).

In practice, it is easier to determine the receiver temperature using the hot- cold calibration. A resistor at room temperature, T_{hot}, yields an output power, P_{hot}. A resistor cooled to T_{cold} with liquid nitrogen gives an output power P_{cold}. These two values define a simple relation between temperature and output power. Using this linear relation, the receiver temperature is given by

$$T_{\text{rec}} = P_{\text{cold}} \frac{T_{\text{hot}} - T_{\text{cold}}}{P_{\text{hot}} - P_{\text{cold}}} - T_{\text{cold}} \tag{1.4}$$

In reality, the limiting sensitivity of a receiver is not only defined by the receiver noise temperature, but also by gain variations and other instabilities. Nevertheless, the receiver noise temperature gives a lower limit to the noise of a receiver that is often the most relevant parameter when planing observations.

1.6 Experimental Setup

This part of the experiment has two sections. In the first section, you will study different components of a receiver and measure some basic parameters of individual components. There are a number of measuring devices available for this experiment such as power meter, spectrum analyzer, and oscilloscope. Tutors will give you some advice on how to use them. Keep in mind that **high precision is not required** for this experiment. The goal is to demonstrate the behavior of the individual components. In the second section, you will work on an upgraded superheterodyne receiver that will be calibrated using a hot-cold measurement.

Keep in mind that some components like amplifiers can only be used in one direction and pay attention to their inputs and outputs. There is an antenna connected to the input of the superheterodyne receiver and you should use a wrench to disconnect it.

1.6.1 Setup 1: Measurement with Individual Components

There are three components that you should work with such as: amplifier, mixer, and band-pass filter, and measure some of their parameters. You will determine some essential characteristics and behaviors in order to become familiar with them. Other parameters like the 1-dB compression point[2] are also important, but they will not be measured in this experiment. Some basic parameters for different amplifiers and filters are summarized in tables 1.1 and 1.2, respectively.

Table 1.1: Parameters of the three amplifiers

Name	Gain (dB)	Bandwidth	1 dB-Compression point (dBm)	Temperature (K)	Function
HF-V1	......	$\approx 2-3$ GHz	6	150	HF-pre-amplifier
HF-V2	......	$2-4$ GHz	13	400	HF-amplifier
ZF-V1	......	$10-500$ MHz	10		IF-amplifier

Table 1.2: Parameters of the two filters

Name	Central frequency	Bandwidth	Insertion Loss	Side Attenuation
HF-F1	$1.8-3.6$ GHz	......	......	......
ZF-F1	150 MHz	≈ 50 MHz	......	......

Amplifier

Definition 1.6.1 An amplifier is an electronic device which amplifies the power of an input signal. It increases the amplitude of the signal using electronic power supply. The gain (the ratio of output power to input) of the amplifier provides some information about the amount of amplification which is more than one.

The most important parameters of an amplifier are the noise temperature and the *gain*. In this experiment you will use three amplifiers: two HF amplifiers working at 2.3 GHz and one IF amplifier working at 150 MHz. The amplifications of all three amplifiers will be measured as follows: a signal generator will be used in the "CW-Mode"(Continuous Wave) as an input (please refer to the 1.7). Select the required frequency, 2.3 GHz for the HF amplifiers and 150 MHz for the IF amplifier, using the transmitter. Make sure that the amplifiers have power supply. Connect the HP power meter to the output of the amplifier to measure the output power.The input frequency of each amplifier should be close to their working regimes. In order to get a pure amplification, you must operate the amplifiers in linear regime.

Exercise 1.1 Determine the gain of the three amplifiers HF-V1 (see Fig. 1), HF-V2 and ZF-V1. Make sure that the receivers are used in the linear regime. How can you test this linear characteristics? ■

Filter

Definition 1.6.2 A filter is a device which eliminates some of the unwanted frequencies or frequency bands of a radio signal.

The frequency behavior of a receiver is in general dominated by the filters. The most important parameters of a filter are the central frequency, bandwidth, adjacent-band rejection and insertion

[2] The 1-dB compression point is the output power that deviates by 1 dB from the linear characteristics. It is a necessity to stay well below this point such as to guarantee a linear relationship between the input and the output power.

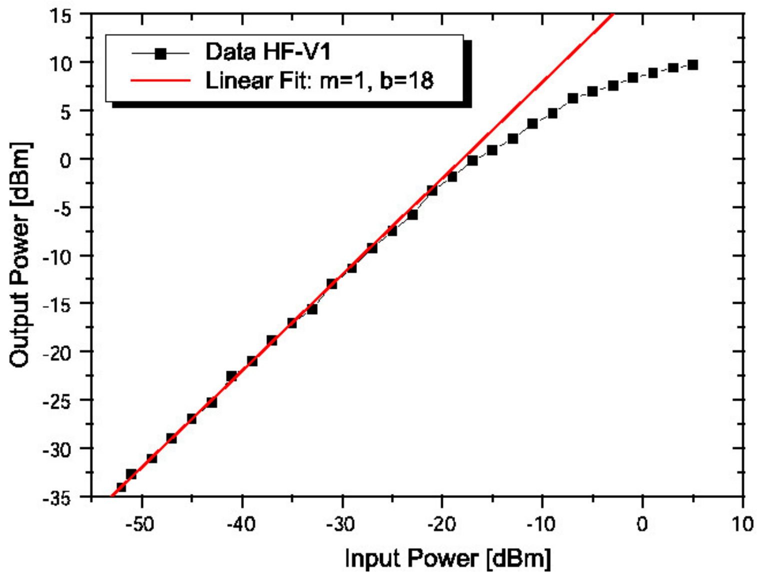

Figure 1.1: Output power of amplifier HF-V1 as a function of input power.

loss. For the determination of these parameters you will use a signal generator in CW-mode at a central frequency of 2.3 GHz an 150 MHz for HF-F1 and ZF-F1 filters, respectively. Power of the input signal is set at 5 dBm.

Exercise 1.2 Measure the input and output power of the filter at different frequencies around the central frequency. Plot the results and determine the insertion loss, the adjacent-band rejection and the bandwidth of the two filters HF-F1 and ZF-F1. ■

Using the signal generator in frequency sweeping mode, you can directly display the bandpass of the filter HF-F1 on an oscilloscope. The frequency sweeps from 2 to 3 GHz in 100 steps of 1 ms. Signal amplitude is -5 dBm; start and stop amplitude is -135 dBm. The oscilloscope will trace swept signal continuously while the signal generator sweeps in loops between the starting and ending frequency. In order to examine the bandpass easier, you should hold the trace after you see the bandpass.

Exercise 1.3 Display the bandpass of the filter HF-F1 on the oscilloscope. Vary the central frequency of the filter. What do you see? ■

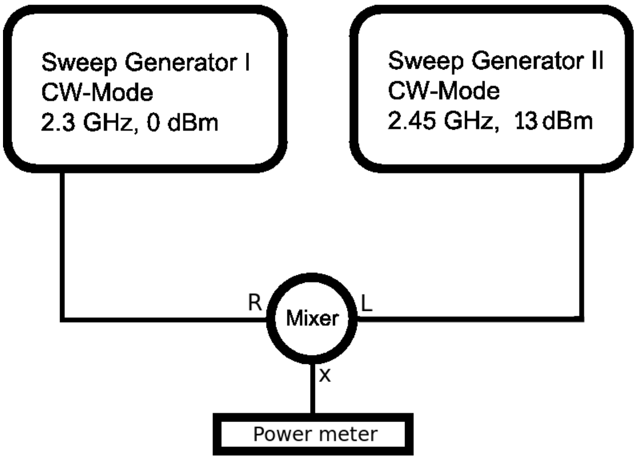

Figure 1.2: Experimental setup for the measurement of the mixing losses

Mixer

Definition 1.6.3 . A mixer is a device which combines two or more radio signals into one output signal.

The two inputs of the mixer are RF signal and a local-oscillator (LO) signal which are down-converted. One of the signal generators (in CW mode) with a power of 13 dBm is operating as the LO. For practical purposes, the lower sideband of the LO is used, and LO frequency of 2.45 GHz has to be chosen. An input power of 0 dBm at 2.3 GHz is fed into the other mixer input using the second signal generator. The output of the mixer is connected to the power meter. The principle setup is shown in Fig.1.2.

Exercise 1.4 Verify that the output power of the mixer depends linearly on the input power of the RF signal. Determine the conversion loss of the mixer on the RF signal. ■

1.6.2 Setup 2: Measurements with a Complete Receiver

For the rest of the experiment you will use the new superheterodyne receiver (see Fig. 1.3). It is constructed from the same components as characterized in the previous exercises (amplifiers, filters, mixer) and has been completely assembled for you to perform the next measurements, no part should be added or removed. Please handle it with caution.

In order to test and calibrate such a receiver, two well defined input powers are required. The input noise signal is provided by a matched 50 Ω resistor (Load). This resistor is first kept at room temperature (use thermometer), and will later be cooled by liquid nitrogen (77 K). The recording will be done on the PC using the Gqrx SDR software (some instructions on how to use the software can be found in the appendix).

Connect the new receiver to the signal generator as indicated in Fig. 1.4, choose a frequency of 1.45 GHz and an input of 0 dBm. **From now on, make sure that the black box connected to the computer will never receive more than -40 dBm**.

Go into the directory *S262_radiolab* and copy the *scripts* folder with a name of your own choosing. You will now save all your files in this directory.

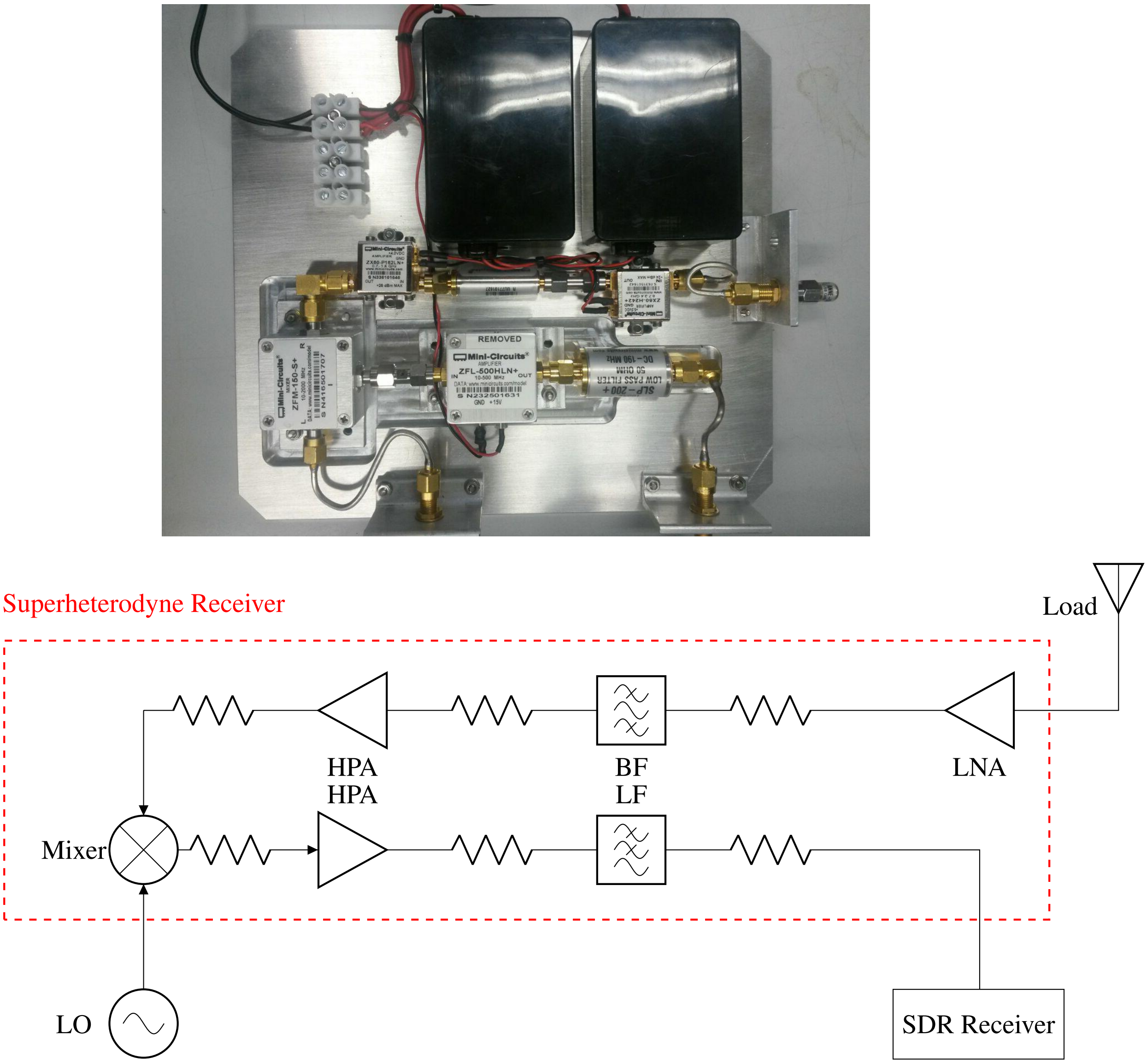

Figure 1.3: Assembled superheterodyne receiver (above) with its schematic diagram (below). The labels are as follows: High Power Amplifier (HPA), Bandpass Filter (BF), Low Noise Amplifier (LNA), Lowpass Filter (LF), and Local Oscillator (LO). Attenuators are used for standing wave ratio (SWR) or Impedance Matching.

Exercise 1.5 Perform the hot-cold calibration. Determine the receiver temperature both graphically and by using the following equation

$$T_{\mathrm{rec}} = P_{\mathrm{cold}} \frac{T_{\mathrm{hot}} - T_{\mathrm{cold}}}{P_{\mathrm{hot}} - P_{\mathrm{cold}}} - T_{\mathrm{cold}} \tag{1.5}$$

■

To do the hot-cold calibration, start recording at room temperature and then dip the resistor into the liquid nitrogen (see the Appendix to know how to record a signal on the computer). Stop recording when it reaches equilibrium (no more bubbles at the surface). Now, in a terminal screen in the working directory you created, run:

```
$./hotcold-power.py filename_yyyymmdd_hhmmss_frequency.raw
```

It will then output the averaged power of each scan on the screen and in the end produce a plot and a text file for your usage. Here the power level recorded on the computer is equal to $10\log\left(\frac{P_c}{P_{ref}}\right)$ or $10\log\left(\frac{P_h}{P_{ref}}\right)$.

We are now ready to determine the noise temperature of an unknown source.

Exercise 1.6 Replace the resistor by the noise diode and use the calibration to determine its noise temperature. ■

You will now simulate atmospheric attenuation by inserting the variable attenuator between the noise diode and the receiver.

Exercise 1.7 Measure the output power as a function of the variable attenuation from 0 dB to 30 dB in steps of 3 dB. Plot the results. Describe and explain the graph. ■

Every time you increase the attenuation, wait for the power level to be stable on the screen (there is a short delay between when you change the attenuation and when it actually appears on the screen) and record the signal for **3 seconds**. Again, use `hotcold-power.py` on **EACH** recording and find the average output power and then plot it as function of attenuation. Describe and explain the graph.

The result can be described in terms of radiation transport, given by the following equations:

$$T_A = T_{sys} - T_{rec} = \frac{1}{L}T_b + \left(1 - \frac{1}{L}\right)T_{atm} \tag{1.6}$$

$$T_A = e^{-\tau}\,T_b + \left(1 - e^{-\tau}\right)T_{atm} \tag{1.7}$$

Here, L is the attenuation, hence $\frac{1}{L}$ is the transmission, i.e. the fraction of the signal passing through the atmosphere. T_b is the brightness temperature of the astronomical object and T_{atm} is the temperature of the atmosphere. The second equation is the solution of the radiation transport equation that you have seen in the lecture. It is the solution of the transport equation for the special case of a homogeneous absorber at constant temperature T_{atm} and optical depth τ. The transmission can be measured by a so-called "sky measurement". The telescopes pointed at a position on the sky away from any astronomical source. The temperature of the atmosphere, T_{atm}, is usually known as all radio observatories are equipped with a meteorological station. With T_A and T_{atm} known, the transmission can now be calculated. With this, the true intensity of a source can be determined.

1.6.3 Setup 3: Radio Spectroscopy

A short introduction to spectroscopy is also feasible with this experiment. A spectrum analyzer is used as a spectroscopic backend. The spectrum analyzer is a simple tool to display the bandpass of the receiver, along with a couple of (man-made) "emission lines". Look at the appendix for more information. There are some lines located outside the bandpass that are FM radio stations. They enter the system because of imperfect shielding of the IF-part. This kind of interference can be very disturbing during an astronomical measurement. For this experiment, the noise diode and the variable attenuation are replaced by an antenna.

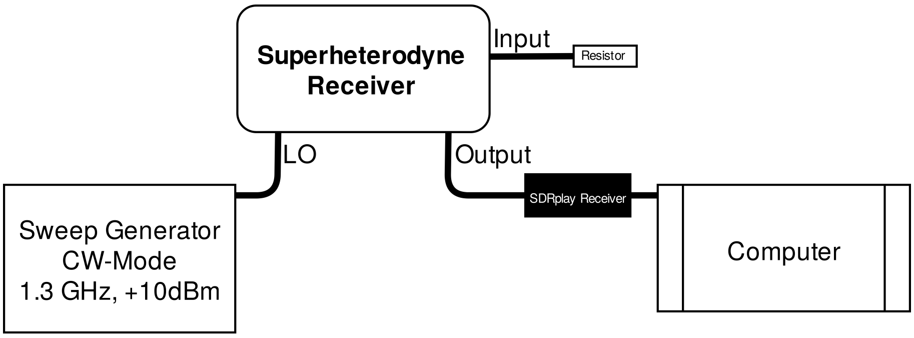

Figure 1.4: Experiment setup with the new superheterodyne receiver

Modify LO power to -50 dBm. Signal generator I plays as an artifact radio source. Set signal generator I to 1.6 GHz and -25 dBm.

Exercise 1.8 Point the antenna at signal generator I. Tune the frequency (CW-mode) of the LO a little bit (less than half of the bandwidth displayed on the spectrum analyzer) and watch the frequency analyzer carefully. What do you see? ■

Connect the receiver output back to the SDRplay receiver.

Exercise 1.9 Record the signal using different recording length times, from seconds to minutes. From the recorded data you could perform the following exercises:

- plot the noise vs recording time
- estimate the rms as a function of recording time
- calculate the integrated line flux
- assuming that the line comes from a cloud in thermal equilibrium, estimate the temperature of that source

■

To help you, run:

```
$./line-detect.py filename_yyyymmdd_hhmmss_frequency.raw
```

which will produce a stacked spectrum text file and plot for a given recording time. Do this for **EACH** recording time.

Exercise 1.10 Reception of external radio signals by a FM Receiver:
What should be the ideal antenna length for efficient transmission of a radio signal at a frequency of 100MHz? Justify your answer. ■

Attach an antenna element to the signal generator and tune the frequency at 100MHz with an amplitude of 5dBm. Turn on the FM receiver and tune it to 100MHz. Comment on your observations.

1.7 HP Power Meter

Figure 1.5: HP Power Meter

Before using the *HP Powermeter* (PM) assure that the PM is calibrated (no RF signal → output power = 0). To calibrate the PM push the *ZERO* button while the RF is switched off. The *HP Powermeter* returns the power value in two units (W and dBm) simultaneously. In this experiment the dBm scale is used. If you want to read an output power on the power meter choose the right **Range** and add value (1) and (2), see Fig. 1.5. In this case the output power results in $(-10)\,\text{dBm} + (-5)\,\text{dBm} = -15\,\text{dBm}$.

1.8 DSO Oscilloscope (Gould 400 Series)

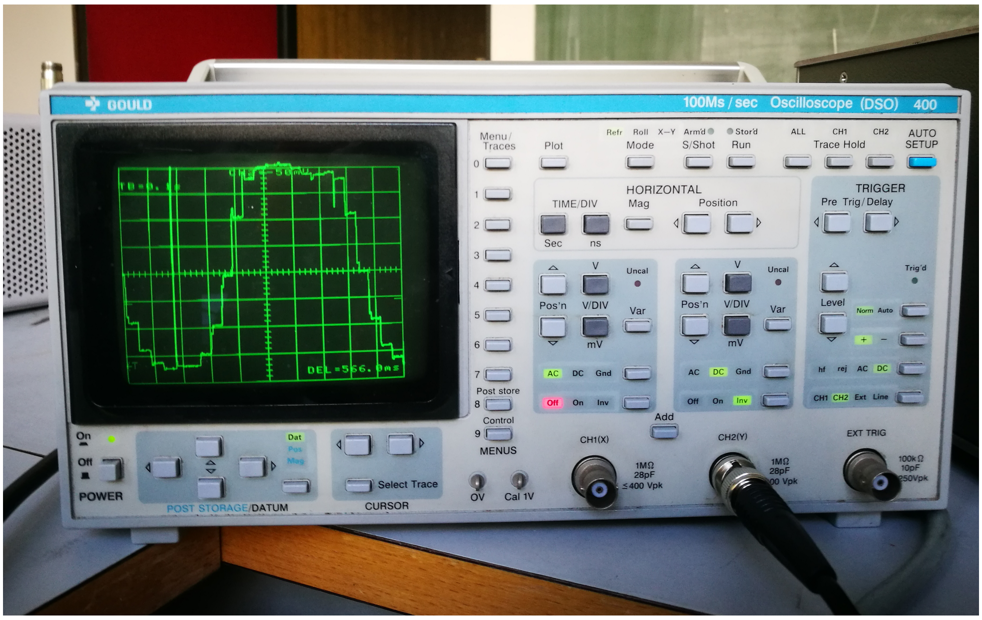

Figure 1.6: Gould 400 Series Digital Storage Oscilloscopes

A brief information about how to work with the oscilloscope in the radio lab is provided below with reference to the user's manual of the DSO Oscilloscope (Gould 400 Series) [3]. A digital storage oscilloscope (DSO) is an oscilloscope which stores and analyses the signal digitally. When switched on with the POWER button, the instrument will go through its automatic self-calibration sequence and then display information. The trace is visible across the center of the screen. At the top will be the sensitivity of the two input channels and the timebase speed. If any input is inactive, information for that channel will not be displayed.

AUTO SETUP: To display an input signal, connect it via either the CHI socket or the CH2 socket and press AUTO SETUP. AUTO SETUP will attempt to arrange the display so that two to five complete cycles appear, with the amplitude set so that the height of the trace is between two and five screen divisions. Also, it selects Auto trigger to ensure that the screen is frequently updated and a trace will be visible. If signals are connected to both channels, the highest amplitude takes priority.

Channel Selection (Off/On/Inv): A channel may be switched on or off with its Off/On/Inv button. If the channel is on, its trace can be displayed in either normal or inverted mode.

- **Off:** The channel is deactivated.
- **On:** The trace is a true representation of the input signal.
- **Inv:** The input signal is inverted before being displayed. If there is any DC component in the signal this will also be inverted and could cause the trace to disappear from the screen. Such an unwanted DC component can be removed by selecting AC coupling. Any vertical shift applied to the trace is not inverted. The trigger point remains at the same point on the waveform regardless of inversion.

Coupling (AC/DC/Gnd): These buttons control the type of coupling between the input signal and the instrument. DC is the most generally applicable, and AUTO SETUP will normally set this

[3] http://www.gucelektronigi.itu.edu.tr/files/dso400.pdf

control to DC, where possible.

- **AC:** This is used to remove any DC component from inputsignals. Suitable input signals (i.e. the bandwidth) are from 4 Hz to 20 MHz.
- **Gnd:** The input signal is internally disconnected from the inputs andthe amplifier grounded. A 0 V reference signal is displayed.
- **DC:** The input signal is directly coupled to the instrument so all frequency components of the input signal will be displayed. The bandwidth will be from DC to 20 MHz.

1.8.1 Horizontal Adjustments:

- **TIME/DIVISION:** These buttons control the sweep rate of the trace. The timebase can be varied from 100 ns/div to 50 s/div in a $1,2,5$ sequence of values. The button marked 'ns' decreases the time/div, the button marked 'sec' increases the time/div. With a timebase of say $200/\mu$s, each horizontal screen division represents $200/\mu$s worth of signal. The timebase is shown near the top of the display - e.g. TB $= 200/\mu$s.
- **Position:** These buttons move all traces to the right or left. The position of the cursor is fixed in relation to the trace so it will move with the applied shift. With x-magnified traces, the cursor can be off the part of the trace displayed on the screen. To bring it back into view use the CURSOR < > buttons.
- **Magnification:** Switches horizontal magnification on or off. When switched on, a x10 expansion is applied to any displayed trace, which will expand around the center of screen. The timebase setting is adjusted to reflect the expansion.

1.8.2 Vertical Adjustments:

Each channel has its own set of vertical controls.

- **VOLTS/DIVISION (V/DIV):** Adjusts the sensitivity of the instrument over discrete calibrated ranges from 2 mV to 5 V per screen division in $1,2,5$ steps. With a x10 probe the ranges are 20 mV to 50 V per division at the probe tip. If the *Uncal* light is on, then these buttons vary the sensitivity continuously.
- **Position (Pos'n):** These move their respective traces up and down the display. If Trace **Hold** is on or a S/Shot capture has been made, any part of the trace which was captured off-screen vertically will be shown by a horizontal line.
- **Variable/Uncalibrated (Var):** When this is set to 'Uncal', the coarse setting of the attenuator remains unchanged, but a variable attenuation is applied to the input signal in the range of 1 to 004. Thus, with an initial setting of 1 V, the actual sensitivity of the channel could be set by this control to anywhere between 1 V and 2.5 V per division. The V/DIV buttons are used to vary the uncalibrated sensitivity.

  Example screen display:
  CH1 $= 5$ V: Channel is set to a sensitivity of 5 Volts per screen division.
  CH1 $= 20$ mV: Channel 2 is uncalibrated and the attenuator is set to a sensitivity greater than 20 mV per screen division.

- **Add:** Displays the sum, or if one channel is inverted the difference, of the input signals. The original traces disappear and the resultant trace is displayed as a Channel 2 trace.

1.8.3 Trigger Control:

- **Selecting Source and Coupling:** The lowest button in the TRIGGER section of the front panel selects the source of the trigger.
  CH1/CH2/Ext/line: Steps through the possible sources of trigger signals. When Ext is selected, the source is the 'EXT TRIG' socket in the lower right corner of the front panel. Selecting line is meaningful only if the instrument is powered from the mains. Triggering is then from an internal pulse having a fixed phase relation to the mains voltage waveform. To change this phase relationship, use the trigger delay buttons.
  hf/rej/AC/DC: Steps through the available trigger coupling options; hf rej is a 15 kHz low-pass filter ('high frequency reject'). All the couplings can be used with any source except Line, with which the input coupling is not selectable.
  Useful frequency ranges of coupling types are as follows:

Coupling	Input
hfrej	10 Hz to 15 kHz
AC	4 Hz to 20 MHz
DC	DC to 20 MHz

- **Level:** The trigger level is the threshold at which the instrument will respond to potential triggers; the trace actually has to pass through the level indicated for a trigger to be valid. The level is indicated on the display by two bars, one on each side of the screen, and is adjusted by the level buttons. For an internal trigger the range is approximately $+/-$ 10 divisions and on external approximately $+/-$ 3 V. If the trigger signal is AC coupled, the level bars will be offset from the actual trigger position on the screen by any DC offset present.

- **Trigger Point (T):** The trigger point is indicated on the display by a 'T' near the bottom of the screen underneath the trigger. An arrow next to the T indicates that the trigger point is off the screen.

- **Slope (+/-):** A trigger is generated when the selected source signal passes through the chosen trigger level. This transition may be either on a rising or a falling edge. The rising edge is considered to be a positive slope and the falling edge a negative slope.
  +/- This button selects positive (+) or negative (-) slope triggers.

- **Trigger Mode (Norm/Auto):** The trigger system operates in either Normal or Auto mode. In Normal mode, display captures can only occur when a valid trigger input has been received. In Auto mode, if no valid trigger has been received for sometime the instrument will generate its own trigger and initiate a capture. This ensures that the screen is constantly updated irrespective of the input signal. However, if valid input triggers are received at a rate of 20 Hz or more, the instrument will start all captures with these triggers and not generate its own.
  Auto/Norm: This button selects which trigger mode the instrument is operating in.
  Trig'd: This LED lights up when the instrument is receiving valid trigger signals.

1.9 Signal Generator

Figure 1.7: Agilent E4421B ESG-A Series Analog RF Signal Generator, 3 GHz

To switch it on, use the button in the bottom left corner. To change a value you can either use the knob or the numerical keypad. If you plug in the numbers using the numerical keypad choose the correct unit using the softkeys (buttons on the right side of the screen). Caution: Pay attention to the “RF ON/OFF” button on the bottom right corner. It should be used to turn RF off during reorganization of your equipment. Avoid using the signal generator in an “unleveled” mode. This happens when the selected output power is too high and will be noted in the screen by a small message next to the “RF ON/OFF” square.

1.9.1 CW-Mode

1. After booting the Signal Generator, it is by default in CW-Mode. To change to CW-mode from Sweep-Mode press the **Sweep/List** Button and switch Sweep off using softkeys.
2. To change the frequency press the **Frequency** Button and choose the frequency.
3. To change the output power press the **Amplitude** Button and select its value.

1.9.2 Sweep-Mode

1. Use **Sweep/List** Button to switch Sweep on using the softkeys.
2. Sweep Type: Step
3. Sweep Repeat: Cont (=continuously)
4. Configure Step Sweep: Select desired Start/Stop frequency
5. Press **Return** Button

1.10 Spectrum Analyzer HM5510

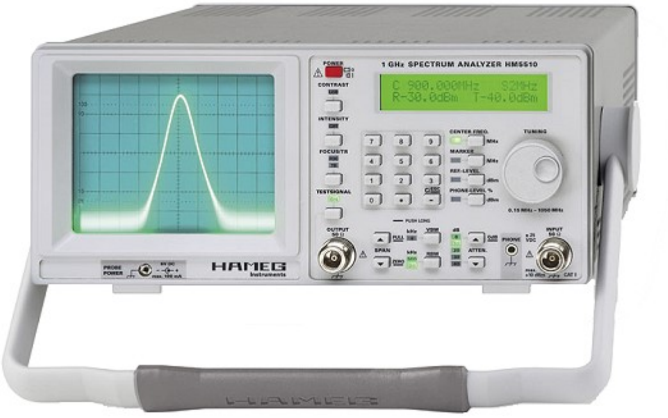

Figure 1.8: Spectrum Analyzer HM5510

A spectrum analyzers monitor the amplitudes of the signal components vs. frequency. The HM5510 is a spectrum analyzer for the frequency range of 150 kHz to 1050 MHz. The analyzed signal must repeat periodically. The analyzer uses the superheterodyne principle. An input signal is mixed with the local oscillator signal using a mixer and is converted to the IF signal. The X-axis amplifier receives a sawtooth sweep signal. The lowest frequency corresponds to the 1st (left) graticule line, the highest to the last (10th).

1.10.1 hints prior to first time operation

The most sensitive part of the instrument is the input stage. It consists of an attenuator, a filter and the mixer. The following input levels must not be exceeded:

- +10 dBm HF with the attenuator at 0 dB
- +20 dBm HF with the attenuator at 40 dB

Higher levels may destroy the input stage. Also remember that signals may contain excessive amplitudes outside the range of the analyzer, i.e. 150 kHz to 1050 MHz. These would not be displayed, will overdrive and possibly destruct the mixer.

1.10.2 How to operate

- Settings: Prior to connecting any signal make sure that any DC content is max. ±25V and that the HF level is +10dBm.
- Attenuator: Set the attenuator first to maximum = 40 dB, the "40 dB-LED" will light.
- Frequency adjustment: Set the CENTER FREQ to 500 MHz (C500.000 MHz) and the SPAN to 1000 MHz (S1GHz). The span is the frequency range displayed on screen, 1 to 1000 MHz.
- RBW (Resolution bandwidth): First use the 500 kHz filter and turn the video filter (VBW) off. Is there only the baseline noise band increase the sensitivity i.e. decrease attenuation.
- The marker is used to derive numbers. Set the MARKER (MRKER LED should light up) to the signal part of interest by turning the knob. Read the frequency (Mxxx.xxx MHz) and the level (Lxx.xdBm) on the LCD display. The level reading automatically takes the reference level (REF.-LEVEL) and the input attenuation (ATTN) into account. Without using the marker the level can be read from the dis-play: the top graticule line is the reference level (R....dBm).

- The TUNING knob can be used to set the parameters of most functions, if the limits are reached an acoustic signal will sound.
- Select the function with any of the keys to the left of the knob,the associated LED will light. Selection of another function will deselect the former.
- The following function are adjustable by the knob: FOCUS/TR, INTENSITY, CONTRAST, CENTER FREQ, MARKERR, EF.-LEVEL, PHONE %

1.11 Gqrx

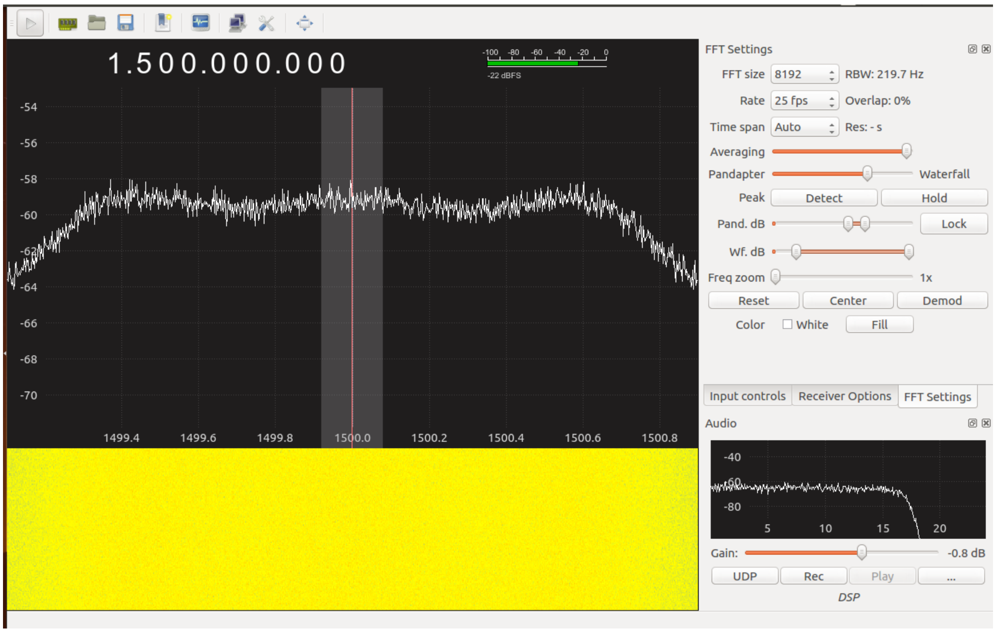

Figure 1.9: Screen shot of the Gqrx SDR software

1.11.1 How to work

GQRX is an open source software defined radio receiver (SDR) powered by the GNU Radio and the Qt graphical toolkit. This software is installed on the PC in the Lab. Open a terminal window and run *gqrx*. First configure the Input/Output of the device using the same settings as shown in Fig. 1.10 (click on the short-cut button just below the Tools menu to open the configuration window). Then make sure that the AGB option (automatic gain control) is off on the main window in the ″input control″ frame. Finally activate gqrx by clicking on the grey start/stop button just below the File menu. You should see the current frequency of the receiver and noise can be heard from your speaker. Below the frequency is the RF spectrum frame around that frequency. Below the spectrum frame is the waterfall frame displaying the spectrum history. On the upper right side of the main window you will find frames with tabs for the input and options of the Receiver, and lower right side frames with tabs for RF signal processing (FFT Settings) and Audio output control. The color of the spectrum display can be changed by the “color” line of the FFT setting tab.

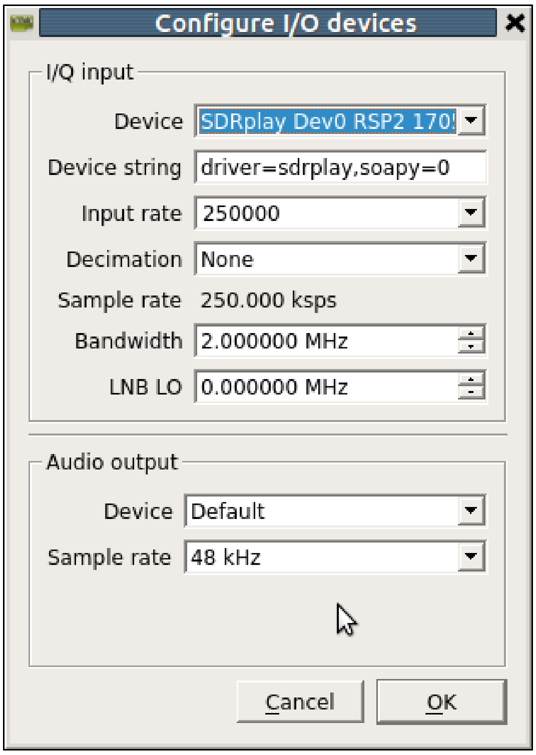

Figure 1.10: Configuration settings

In the left part of the main window starting from the top you find: the current frequency of the receiver (here it should be 150 MHz), below the frequency is the RF spectrum frame around that frequency and finally the waterfall frame displaying the spectrum history.

You can change the frequency scale by placing the mouse pointer on the frequency scale at the bottom of the spectrum window and then click+drag right or left. You can reset the display with the ″Zoom″ ″R″ button in the FFT Settings frame.

To record a signal, select tools, I/Q recorder, select a location (for instance radiolab/data/) and start recording. The recording time is displayed on the screen, don't forget to write it down after recording. The audio file name format will be: `gqrx_yyyymmdd_hhmmss_frequency.raw`

- yyyy is the year
- mm is the month
- dd is the day
- hhmmss the start hour, minutes,seconds
- frequency is the hardware in Hz

Once you have recorded an image you can visualise it with the provided ancillary python scripts.

For more information, please refer to the following webpage:
`http://gqrx.dk/doc/practical-tricks-and-tips#start`

Part Two

2. Setting up a twin radio interferometer

2.1 Introduction

Radio telescopes are great tools to study radio emission from stars, galaxies, quasars, and other astronomical objects with the wavelength between about 10 m (30 MHz) and 1 mm (300 GHz). The incoming radio waves have to pass through the ionosphere. This layer of the atmosphere causes the signals to be fluctuated irregularly due to the refraction caused by small-scale fluctuations in air density because of temperature gradient, particularly at wavelengths longer than about 20 cm (1.5 GHz). This phenomenon is known as *scintillation* which is identical to the twinkling of stars seen at optical wavelengths. As the wavelength increases, the absorption of cosmic radio waves becomes more significant. The ionosphere is opaque for the radio signals with the wavelength more than 10 m. So, it is very difficult to observe radio sources at these wavelength from ground-based radio telescopes. On the other hand, for the wavelength below a few centimeters, absorption is critical in the atmosphere. At wavelengths shorter than 1 cm (30 GHz), a few specific wavelength bands can be observed from the ground. However, in the range of 1 to 20 cm, the atmosphere creates only a minor distortion in the incoming radio signals. These effects can be corrected efficiently using sophisticated signal processing and data analysis.

All radio telescopes have two basic components such as a large radio antenna and a sensitive radiometer or radio receiver. The **sensitivity** of a radio telescope is a very important property for observation which depends on the surface area and efficiency of the antenna in addition to the sensitivity of the radio receiver (used to amplify and detect the signals). The sensitivity also depends on the bandwidth of the receiver [1] for broadband signals [2]. As radio signals are very weak, radio telescopes are usually very large. In addition, man-made radio interference caused the cosmic radio signals to be masked and hard to detect. The limiting sensitivity of a radio astronomical

[1] Bandwidth (BW) of a receiver is the range of frequencies (measured in Hz) involved in the reception of an electronic signal.

[2] A wide band of frequencies for data transmission in which multiple signals are carried with a medium (cable/wire). This broadband is often divided into channels or "frequency bins".

receiver can be calculated via the **radiometer equation**

$$\Delta T = \frac{T_{Sys}}{\sqrt{\Delta\nu \cdot \tau}} \tag{2.1}$$

where T_{Sys} is the system temperature, $\Delta\nu$ is the bandwidth of the correlator (in Hz), and τ is the integration time (seconds).

A radio reflector consisting of a parabolic antenna, which is called dish or filled-aperture telescope, is the most common type of radio telescope and it focuses the incoming radiation onto a small antenna, which is called feed. The typical feed in a radio telescope, in general, is a waveguide horn by which the incoming signal is transferred to the sensitive radio receiver. To gain the best feasible sensitivity, amplifiers with very low internal noise are used.

Some radio telescopes have parabolic surface which is *equatorially mounted*, with one axis parallel to the rotation axis of the Earth. As the Earth rotates, these telescopes follow the a position in the sky by moving the antenna about a single axis parallel to the Earth's axis of rotation. A computer is used to control these telescopes.

In a simple radio telescope, the receiver is located directly at the focal point of the parabolic reflector (We can also see focal point in prime focus in some advanced radio telescope e.g. Effelsberg 100-m Radio Telescope). Cables along the feed support structure are used to transfer the detected radio signals to a place which can be recorded and analyzed. Secondary focus systems also have been used to improve the gain over that of a simple parabolic antenna. In newer designs of radio telescopes, the feed or secondary reflector is located *off axis* and does not block the incoming signal.

There are various factors for the performance of a radio telescope including the accuracy of a reflecting surface; the effect of wind loads [3]; thermal deformations which bring about differential expansion and contraction; and deflections due to changes in gravitational forces when the antenna is pointed to different parts of the sky.

It is of crucial importance when a reflector departures from a perfect parabolic surface for a few percent of **the wavelength of operation**. The smaller structures can be constructed with better precision than the larger ones, hence built up radio telescopes with diameters between a few tens of meters and 100 meters are designed for millimeter and centimeter wavelengths, respectively.

The **angular resolution** or the **smallest angular scale** of a radio telescope is very important because it provides information about the ability of the radio telescope to differentiate the fine details of the sky. For a single dish telescope, it is equal to the wavelength of observations over the diameter of the dish.

$$\theta = 1.22\frac{\lambda}{D} \tag{2.2}$$

For the largest antennas, working at their shortest operating wavelength, θ is around one arc minute (close to that of naked human eye at optical wavelengths). As the wavelengths of the radio telescopes are much longer than that of optical ones, the sizes of the radio telescopes must be much larger than the optical one to fulfill the same angular resolution.

The angular resolution of a twin interferometer, however, is equal to the wavelength of observations over the distance B between two antennas.

$$\theta = 1.22\frac{\lambda}{B} \tag{2.3}$$

The distance between two antennas is called the **baseline**. Long baselines are used for collecting data about the small scale structure of the source, and vice versa. The smaller the mirrors or the closer the antennas, the larger structures can be resolved. **Diffraction limit** of an interferometer

[3] Various types of forces exerted on the telescope by wind

is the smallest detectable angular scale. **Largest angular scale** can be obtained by the shortest baseline in the configuration of an interferometer. The sensitivity of an interferometer is in the range of the diffraction limit and the largest angular scale. For a single dish telescope, the angular resolution of the antenna determines which size scales on the sky can be sampled. However, in an interferometer with more than two antennas, the size scales on the sky can be sampled based on the projected distances between pairs of antennas. If a structure in the sky has a size scale greater than that detected by smallest baseline, the structure cannot be detected at all.

The largest scale structure that can be detected by an interferometer is called the **maximum recoverable scale**.

$$\theta_{MRS} = 1.22\frac{\lambda}{B_{\min}} \tag{2.4}$$

Without paying attention to the maximum recoverable scale, there will be some missing parts in the observed image compared to the true image of the sky, and there is no information about the structures larger than the maximum recoverable scale. As a consequence:

- The angular resolution determined the largest baselines
- The largest angular scale determines the smallest baselines

In radio astronomy, firstly, the distortion caused by the atmosphere is less important than at optical, therefore the theoretical angular resolution of a radio telescope may be gained in practice. Secondly, radio signals are distributed simply over large distances without distortion, therefore it is feasible to construct radio telescopes of essentially unlimited dimensions. The challenge for building new radio telescopes is to continually increase angular resolution.

The principles of interferometry could provide a very effective way to achieve high angular resolution. In this technique, a very large effective aperture can be synthesized from a number of small elements. In a simple two-dish radio interferometer, as the Earth rotates, the signals from a point source alternately arrive in phase and out of phase. There is a difference between the path from the point source to either of the two elements of the interferometer. Identical to the optical interferometry, this causes to create interference fringes. For radio sources with finite angular size, the path length to the elements of the interferometer varies across the source.

Each interferometer pair measures one "*Fourier component*" of the **brightness distribution** of the radio source. As the Earth rotates, movable antenna elements can sample a sufficient number of Fourier components to synthesize the impact of a large aperture and reconstruct high-resolution images of the radio sky. It needs a large number of Fourier transforms to produce images from the interferometric data using high speed computers equipped with high speed CPU and GPU, **Fast Fourier Transform** (FFT) algorithms, and a mathematical technique that is especially suited for computing discrete Fourier transforms (DFT). *Aperture synthesis* or earth-rotation synthesis is a type of interferometry which combines the output signals of a collection of radio telescopes to produce the radio images with the same angular resolution. To remove the spurious responses from a celestial radio image caused by the use of discrete, rather than continuous, spacings in deriving the radio image "CLEAN" technique is used. Using the concept of self-calibration, errors in a radio image due to uncertainties in the response of individual antennas in addition to small errors created by the propagation of radio signals through the terrestrial atmosphere can be removed. This is the way to achieve outstanding angular resolution and image quality in radio astronomy which is not possible in any other wavelength band.

Exercise 2.1 Which property of the telescope can affect angular resolution and image quality? ■

Exercise 2.2 What is the difference between the wavelengths of operation at radio telescopes with small and big parabolic surfaces? ■

This part of the experiment, deals extensively with a single-dish, interferometry and aperture syntheses. First you will work with a single-dish radio telescope to observe the Sun. Second, you will add another dish to the set up and make a twin radio interferometer and observe the fringe pattern.

2.2 The educational twin-interferometer of the University of Bonn

It is hard, or impossible, to have access to a radio interferometer for university courses. University of Bonn is one of the universities in Germany which offers a professional interferometer for educational laboratory experiment. The twin-interferometer at the Argelander Institute for Astronomy has been developed as a simple and well-operated radio interferometer suitable for graduate astronomy lab course. It operates at radio wavelengths to see the fringe pattern of the interferometer by observing the Sun. It can resolve and measure the diameter of the Sun, a nice daytime experiment which is applicable even in the partial cloud weather. This twin-interferometry has been provided to train the further generation of young astronomers.

2.3 Mathematical background of the twin interferometer

Please take a look at the 10th chapter of the Radio Astronomy tools, applications and impacts lecture notes by Uli Klein. In this experiment, we use phase-switched interferometer.

2.4 The equatorial coordinate system: α , δ

There are several coordinate systems used in Astronomy to specify the positions of celestial objects. These have been introduced because of the variety of problems to be solved. The direction of any celestial object can be defined uniquely at a given time by particular *great circles*. The origin of each system also depends on the particular problem in hand, and if it is the observer's position on the surface of the Earth, the Earth's center, or the Sun's center, it is called a topocentric system, a geocentric system, or a heliocentric system, respectively. The time system used in each system depends on the Earth's rotation or the movement of the Sun. In figure 2.1, the observer at O, northern latitude ϕ, can define the point as the **Z**enith, directly opposite to the direction in which a plumb-line hangs. All stars trace out circles of various sizes centered on the north celestial pole (P). Polaris, the Pole Star, is around one degree from the pole. The altitude of the pole is the latitude of the observer. The great circle from the zenith through the north celestial pole meets the horizon at **N**orth and **S**outh.

Exercise 2.3 How can you prove the equality of the altitude of the north celestial pole and the latitude of the observer?
Hint: Draw the Earth, indicate the path of the starlight towards two position, north pole and the position of the observer, and show that they are parallel. ■

Exercise 2.4 How many full moons can be laid side-by-side within Polaris' circular path about the north celestial pole.
Hint: the angular diameter of the Moon is $\sim 30'$ ■

In *the equatorial system*, the **O**rigin is at the center of Earth. If the plane of the Earth's equator is extended into the celestial sphere, it will cut it in a great circle called the *celestial equator*. This circle intersects the horizon circle in two points **W**est and **E**ast. The position of X in this system are specified by the **Right Ascension**, α, and the **declination**, δ. The poles of the celestial equator and the horizon are points **P** and **Z**, respectively. Declination is measured from 0° to 90° north and south of the equator (north takes the positive and south takes the negative). Right ascension is measured along the equator from γ eastwards from 0^h to 24^h or from 0° to 360°. A **meridian** is any great semicircle passing through P. An **hour angle (HA)** is the angle between the meridian through the celestial object X and the observer's meridian (the one which pass through P and zenith). It is measured from the observer's meridian westwards to the meridian through the star from 0 h to 24 h or from 0° to 360○.

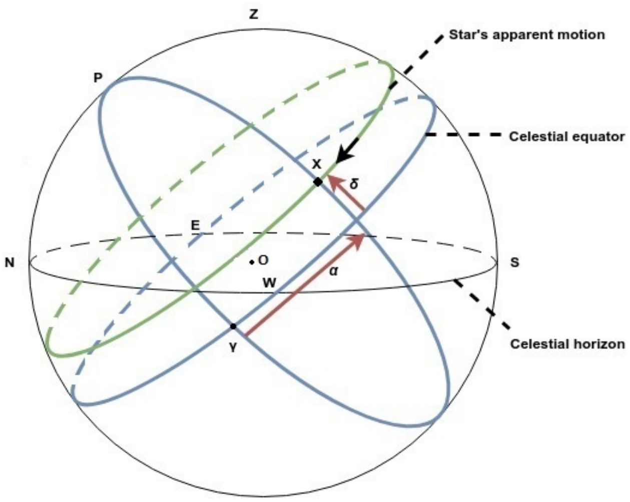

Figure 2.1: The equatorial system: Z is the zenith, O the observer, P is the north celestial pole and OX the instantaneous direction of an object in sky. The great circle through Z and P cuts the celestial horizon at the north (N) and south (S) points. Celestial equator cuts the horizon in the west (W) and east (E) points. The declination, δ, of the star is the angular distance in degrees of the star from the equator along the meridian through the star and is constant with time. The right ascension, α, of the star is the angular distance of the γ point from the intersection of a star's meridian and the equator.

2.5 The radio emission from the Sun

The Sun is the brightest radio source in the sky. It is a **thermal source** and emits radio emission more at high frequencies. There is also a strong emission at lower frequencies.

Exercise 2.5 Solar atmosphere has three main layers: the photosphere, the chromosphere and the corona. What kind of emission does each layer emit? Which layer(s) does(do) emit in radio wavelengths? ■

Exercise 2.6 What is the origin of the radio emission of the corona? ■

Exercise 2.7 Plot the flux density vs. frequency for three different sources (e.g. 1000, 4000, 8000) and place the solar emission profile on it. Does the Sun have a perfect black body radiation? ■

Exercise 2.8 What is the difference between the radio emission of the active Sun and the quiet Sun? Locate both in the plot. ■

The radius of the Sun varies as we change the study frequency. For very low frequencies (below 0.1 GHz) and very long wavelengths (> 3 m), the radius of the Sun is greater and the Sun appears brighter in the center. As we go away from the center, the brightness decreases and after several solar radii it vanishes. For frequencies in the range of 0.1 GHz to 3 GHz, the solar radius is still greater than its optical counterpart. For frequencies above 3 GHz, the solar radius is identical to the optical one to its optical counterpart and its brightness is uniform.

Exercise 2.9 In which case can we see the Sun bigger in size? Observing the photosphere or the corona? ■

2.6 Instrumentation and experimental set up

We utilized two commercial broadcast satellite dishes and receivers operating at radio **X-band**. They have been constructed in our machine and electronics shop.
We will describe how to prepare and operate the AIFA radio interferometer.

2.6.1 Checklist

The twin interferometer consists of:

1. Two commercial parabolic antennas of 90 cm diameter with equatorial mount
2. Two commercial Low-Noise Converters (LNC's) with primary focus feed horn, RF amplifier, filter, mixer and IF amplification
3. A common oscillator system with phase shifter
4. Two total power channels
5. A complex correlator with phase switching
6. A micro-controller between the PC and the motors of each telescope for the mount drive
7. Two power supplies for the mounts drive
8. The cycle control, in particular of the phase switch. It is a micro-controller which collects data from the correlator
9. A PC for data collection and data analysis
10. Toolbox containing: a slot screw driver, Allen tool, connecting cables
11. A rack containing PC and items 2–10
12. An extension cord reel and two power strips
13. Two four-wheeled push-cart on which the mounts are resided (mobile tripod)
14. Two computer chairs on which you can sit and work
15. A metal ramp

These items are in the forth floor of the AIFA building, the room next to the dome. Tutors will show you how to set up and operate the telescopes.

Note that to cart the rack outside of the room, you should use the four handles on two sides of the rack. You will need a metal ramp to move it outside on top of the roof. To move the telescopes outside, you must take care of the parabolic antennas and LNC's. Also note that there should be a visible shadow on the ground and also not too strong wind (< 15 km/h) during the interferometry. Tutors will give you the necessary advice.

2.6.2 Preparations

We are going to carry out a transit observation of the Sun with each telescope and see the fringe pattern formed by the interferometer. To do so, first we have to check the weather condition and then take all the equipment to the desired setup location, in the south side of the dome.

- **Weather:**
  1. Make sure to check a reliable weather website (or multiple) and assess the chance of rain and clouds for the day. Light clouds shouldn't be a problem, as long as there is enough sunlight to cast shadows. If you notice rain clouds appearing, or the sky gradually being covered by a layer of thick clouds, pack up the equipment and go inside.
  2. It's windy on the roof and the antennas can oppose quite some resistance to airflow. Be careful with carrying and placing the antennas during strong winds.
  3. Dress accordingly for the weather.
- **Telescope:**
  Once the weather checks are done, begin taking out the telescope parts: The rack, antennas and mounts are located in the telescope's dome annexe and storage room, respectively. You will have access to them if tutors unlock the observatory's door. The followings are necessary steps describing the assembly process:
  1. Take out the rack, using the metal ramp on the roof
  2. Remove the antenna from the first mount, place it outside resting on the concrete cylinder close to the lightning rod, in such a way that it is not resting on the side of the dish, possibly deforming it.
  3. Remove the equatorial mount from the mobile tripod and place it outside.
  4. Remove the equatorial mount adapter ring from the mobile tripod and install it outside on the fixed tripod. You need Allen wrench to turn the Allen screws.
  5. Place the equatorial mount on the adapter ring on the tripod outside. Fix the mounts in position and tighten the screws. The mounts must not slip. Test them by yanking each mount back and forth a couple of times. It shouldn't move relative to the tripod.
  6. A small bull's eye level is incorporated into each mount. Try to roughly level the mounts using them. The tripods are almost aligned EW - NS, so it is possible to align the mount with the north direction.
  7. There is a latitude marking on each mount and you should increase the hight of the mount by the latitude of your location which is $\sim 50.7°$
  8. Attach the antenna to the equatorial mount such that the antenna is facing towards the west and counterweights are below the level of the antenna when the telescope is in operation, and that no cable ports are facing upwards.
  9. For each antenna, you should balance the antenna on the declination axis, which is the motion around the counterweight shaft. Then balance the mount around the Right Ascension axis. Carefully let the antenna flop to the side, which will happen because the antenna is putting weight on its end of the RA axis. <u>Don't let it free-fall!</u> Help it down gently with your hands.
  10. Be careful not to drop anything from the rooftop.
  11. Connect the cables between antennas and the rack (make sure the RA and Dec cable are properly connected to the mount - i.e. not inverted).
  12. Take the yellow Internet cable out of the window and connect it to the computer in the rack.
  13. Run the extension cord to the nearest outlet and plug the power strip (on the rack) into it.
  14. You should now hear the buzzing sound of the radio receiver.

15. Turn on the computer.

2.7 Observation

- The two mounts are already set to the latitude of Bonn ($\sim$ 51° N). In order to align them to the north pole more precisely, try to have the mounts follow the legs of the tripod that are pointing towards NS.
- In the time between pointing the antennas and issuing a command to the telescope, the hour angle of the Sun increases. In order to save the time, make the command ready before orienting the dishes so, all you have to do is pressing Enter key.
- Sit behind the computer. Open two independent terminal windows, each of them would occupy half of the screen.
- Source Python 2 environment in both terminals and run the following commands:

```
$source activate py2env
$cd ./scripts/twintel
$ipython
```

- Run the following command in the left terminal window:

```
execfile("twin_control.py")
```

- Press Enter key after you get a warning message.
- Run the following command in the right terminal window:

```
execfile("display_twin.py")
```

- The information of the two telescopes such as the date, time and position of telescopes will be displayed. Note that the positions are declarative, the mounts do not know where they are pointing unless inform them with initial coordinates.
- If you could not see the display, run `CTRL + C` on the right window and start it again.

2.7.1 Declination scan

To do a declination scan of the Sun, use the detector's shadow on the surface of the dish to align it, as is illustrated in figure 2.2. Th initial position of the dish is shown in figure 2.3.

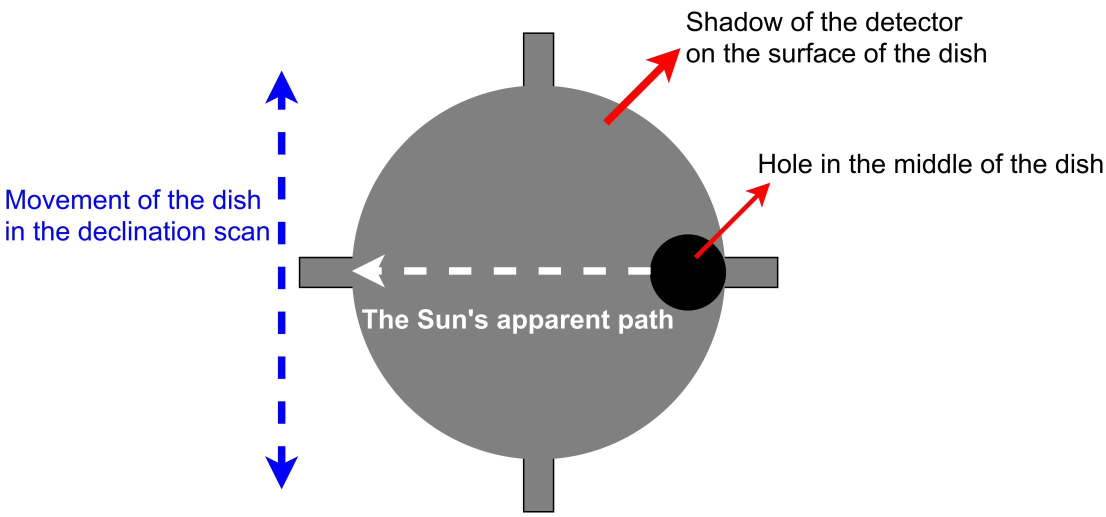

Figure 2.2: Initial position of the dish for the declination scan

- Run the following command to tell the telescope to scan up and down in declination, while not tracking in RA.

```
dec_scan
```

This will let the Sun slowly drift through the center of our field of view, while we scan up and down in Dec, resulting in a “raster” scan of the Sun, as it is shown in the figure 2.3.

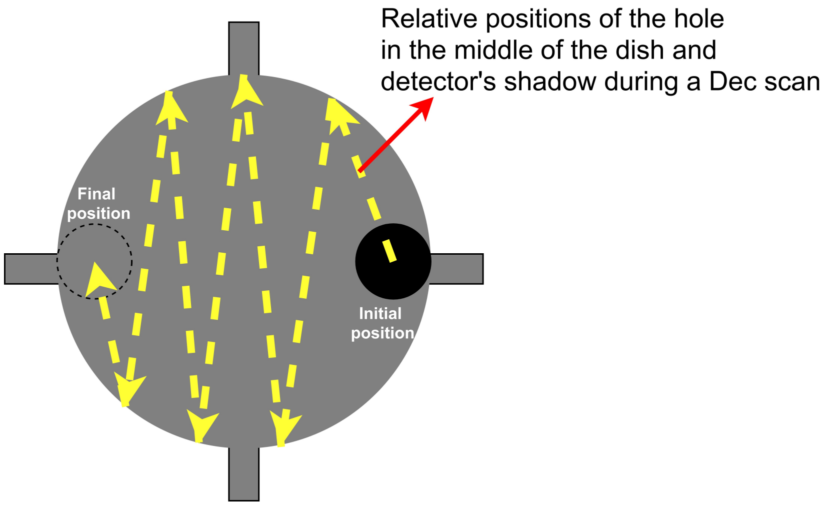

Figure 2.3: The path of the Sun, in the middle of the dish, with respect to the detector’s shadow on the surface of the dish during the raster scan

- After alignment of the two antennas, run the following command:

```
dec_scan(telescope_objects = [tel1 ,tel2],receiver_object=
[rec1],sideofsquare = 6*u.deg,density=50)
```

The first argument *telescope objects* supplies the two telescope objects that have to do the scan, the second argument *receiver object* provides the receiver object that receives the data. All these objects have been declared at the beginning of the program (look inside `twin_control.py` if you are curious). The argument provides the length of the declination scan in degrees (note the u.deg). Usually 5-6 degrees would be good. The argument *density* controls how many movements the telescope does. Between 20 to 50 should be enough. Stop the scan when all surface area of the shadow is scanned and the hole is located at the final position (looks at the figure 2.3).
- To stop the scan, use `CTRL + C`.
- Run the following command to stop the telescopes

```
stop_all(tel1 ,tel2)
```

- Exit both programs with `CTRL + C` and restart ipython.
- Data is stored in $movedata_out.txt$ file. Make sure to change the name of this file after each scan. The software will always append data at the end of the output file, unless you set the output filename to something different from the beginning of scan, like so:
`rec1.output_filename = "yourfilename.txt"`
in which data will be appended to the file `moveyourfilename.txt`.
- If you open the file with an editor (e.g. Vim), you will see the data set into columns such as time, pointing coordinates, flux of antenna A, Q component of the visibility, I component of the visibility [4], flux of antenna B, counter number supplied by the microcontroller.

[4] $|V| = \sqrt{Q^2 + I^2}$

- You can write a program to plot the data. However, we provide a Python file which plots the data: `plot_data.py`.

2.7.2 Still scan

To do a still scan, place the detector's shadow tangential to the hole in the middle of the dish and fix the clamps of the mounts, as is shown in figure . The still scan starts scanning without moving the antennas and let the Sun pass in front of both detectors and store the data.

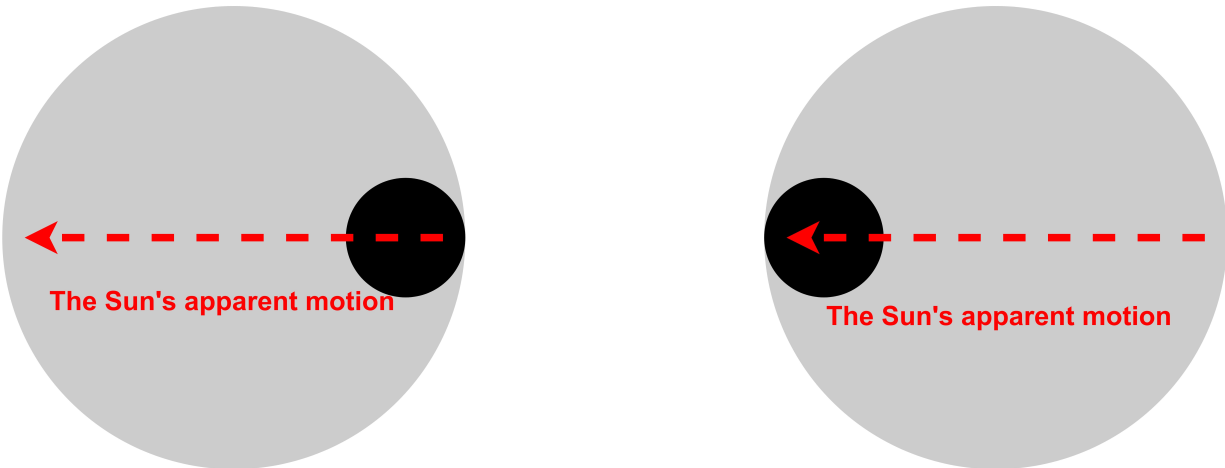

Figure 2.4: The path of the Sun, in the middle of the dish, with respect to the detector's shadow on the surface of the dish during the still scan

- Issue the following command in the command interface:

  ```
  rec1.scan_still(scan_time = 1500*u.s)
  ```

  The parameter *scan time* tells you how long the scan should last. In our experience, 20-30 minutes should be enough. Here we used 1500 s (which is 25 min). You can also supply the time in minutes and use u.minute i.e. $25 * $u.minute.
- The data will be saved to `stilldata_out.txt`, unless you set the output filename from the beginning to something different, like so:
  `rec1.output_filename = "yourfilenamehere.txt"`
  in which data will be appended to the file `stillyourfilenamere.txt` (still because the telescope doesn't move during this scan).
- You can look into the data and make the appropriate plots with your favorite plotting software, or use `plot_data.py`.

2.8 Data reduction with the AIFA twin interferometer

2.8.1 Understanding the data: brief introduction

The interferometer has two operating modes:

- Declination drift scan mode: both telescopes scan an area of the sky moving "up" and "down" in declination for several degrees, while not tracking along the RA axis. The result is an image of the scanned object, as it passes in front of the telescopes.

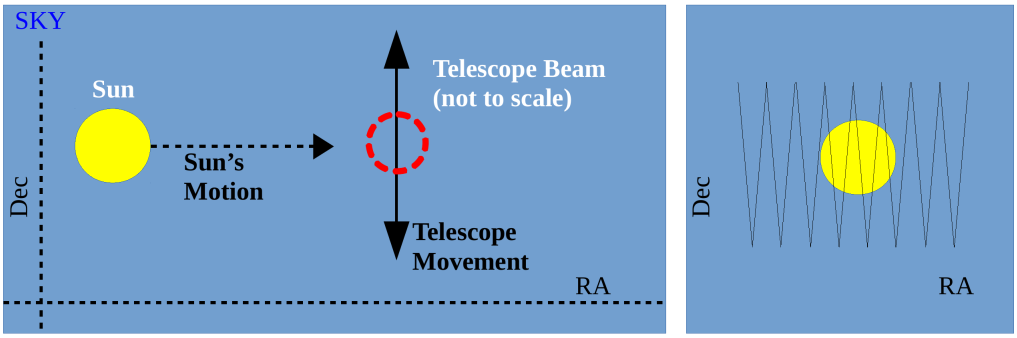

Figure 2.5: Declination drift scan mode

- Simple drift scan mode: both telescopes are pointing to a position the Sun will be in after approximately 30 minutes or so. The interferometer observes the sun entering and crossing its field of view. This way one can more easily observe the fringe pattern of the interferometer.

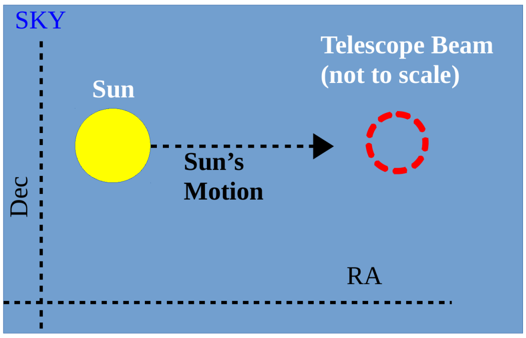

Figure 2.6: Simple drift scan mode

2.8.2 Understanding the data: the raw data

The telescope outputs data from both antennas and the correlator. The data are saved in one of two text files, one for each mode of operation described above.

```
2018-10-17 13:19:08 13:04:41.0675 -02:23:12.1875   178   424   444   153 1
2018-10-17 13:19:08 13:04:41.0675 -02:23:12.1875   176   421   443   150 2
2018-10-17 13:19:08 13:04:41.0675 -02:23:12.1875   176   421   441   152 3
2018-10-17 13:19:09 13:04:41.0675 -02:23:12.1875   176   423   444   151 4
2018-10-17 13:19:09 13:04:41.0675 -02:23:12.1875   177   422   443   152 5
2018-10-17 13:19:09 13:04:41.3241 -02:20:43.3594   177   421   442   152 6
2018-10-17 13:19:09 13:04:41.3241 -02:20:43.3594   176   419   441   150 7
2018-10-17 13:19:09 13:04:41.3241 -02:20:43.3594   172   409   432   148 8
2018-10-17 13:19:09 13:04:41.3241 -02:20:43.3594   176   421   443   150 9
```

Figure 2.7: Format of the raw data

Each line represents an individual measurement. The first two columns record the date and time at which the measurement was taken, the third and fourth columns are the RA and Dec of the measurement. The next four columns, from fifth to eighth, are the signal intensity in Antenna A, the real component of the visibility (Q), the imaginary component of the visibility (I), and the intensity of the signal in Antenna B, respectively. The last column is a counter supplied by the receiver which gives the number of the recordings since the beginning of the ongoing observing session.

Assuming we have the data from a declination drift scan. If we plot the RA vs. Dec of the telescope beam, as it is indicated in the figure 2.8 (left), we obtain a zigzag pattern in the sky. The arrows indicate how the time (or counter) variable increasing during the scan. When the Sun is in the telescope's beam, we get a signal. The portions along the path of the telescope's beam that get a signal are marked in red in figure 2.8 (right). If we simply plot the intensity vs time from our data, we expect a plot similar to the Amplitude vs. Time.

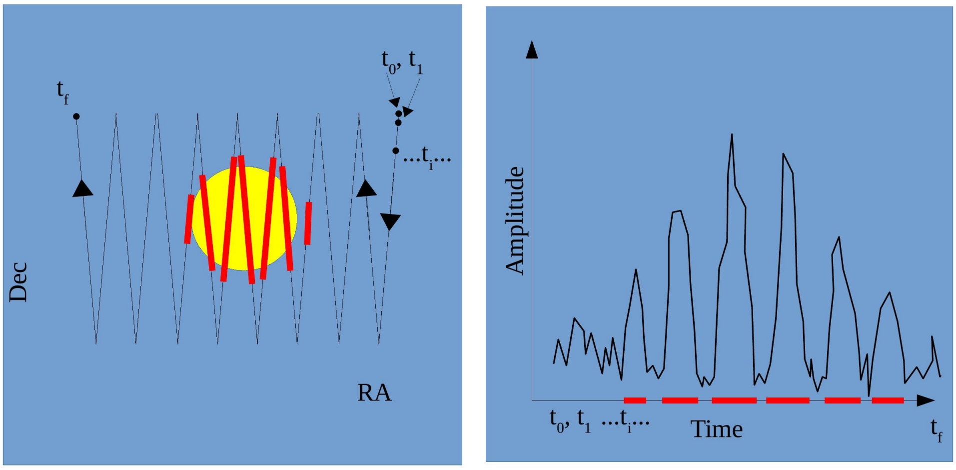

Figure 2.8: The RA vs. Dec plot (left) and the Amplitude vs. Time plot (right) of the telescope beam during the declination scan of the Sun

2.8.3 Understanding the data: data processing

The raw data is plotted in figure 2.9 (a). We can see there is a lot of noise in the image (a), but we can discern the overall shape as similar with the previous drawing. Zooming in on one of the peaks (b), we can take a look at the noise. We see that the noise is regular and introduces large values. This noise has to be cleaned before continuing. When the data have been denoised, we can take a look at the data again (d). We can now see clearly the variation in intensity as the Sun moves through the beams of the telescopes.

After the noise has been removed, we can create a 2D image of the Sun. For every measurement in the intensity vs. time plot, we also have the RA and Dec coordinates. We display the telescope pointing in figure (f). The intensity from plot (d) is recorded along that path in (f). To obtain a 2D image we create an empty 2D grid of spatial coordinates that covers our field of view (i.e. the zig-zag pattern). Using the RA, Dec, and intensity values from our data, we interpolate the missing values on the 2D grid, the result is a 2D image of the Sun as indicated in figure 2.10.

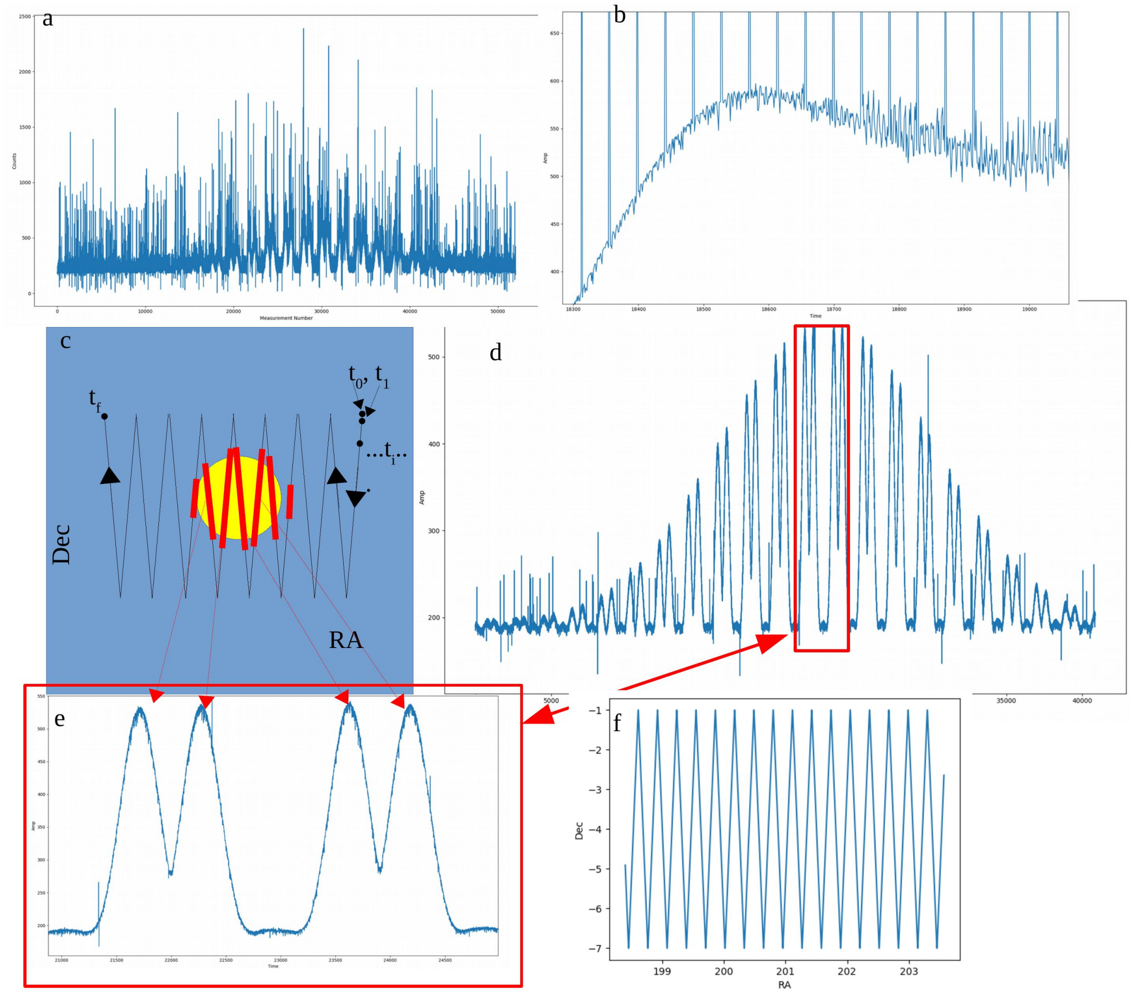

Figure 2.9: Data processing for the declination scan observation of the Sun

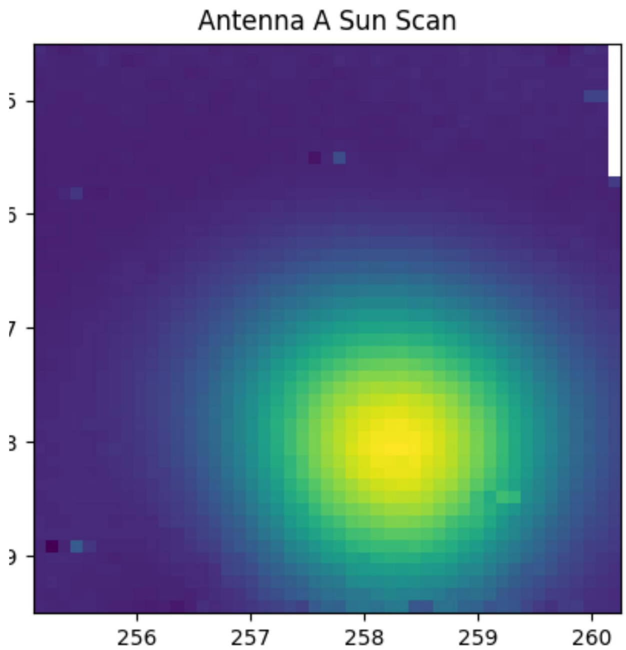

Figure 2.10: 2D image of the Sun after the data processing is finished. The units for each axis are in degree.

For further clarifications, use the attached python script, by copying and pasting each step at a time from the script file into ipython.

2.8.4 Hands on Data Reduction

- Use ipython with python2.7
- Make sure all dependencies are met
- Use a faster computer for faster results
- Copy and paste the code into ipython or a script file

```
# PROCESSING DECLINATION DRIFT SCAN DATA
from datetime import datetime
from time import time
import numpy as np
from astropy.io import ascii
from astropy.table import Table
from astropy.coordinates import SkyCoord
import astropy.units as u
from scipy.interpolate import griddata
import matplotlib.pyplot as plt
import pickle
import sys
datain = []

# STEP 0
# copy paste chunks of this code into the ipython console to see how it works
# read the datafile - put your data file name between the quotes.
try:
    datatab = ascii.read("")
except Exception,e:
    print e
# assign the columns to arrays
# coords = coordinates of the pointings
# fluxa and fluxb are fluxes from ant 1 and 2
# Q and I are components of the visibility
coords = [SkyCoord(d[0]+" "+d[1],unit=(u.hourangle,u.deg)) for d in
zip(datatab['col3'],datatab['col4'])]
fluxa = list(datatab['col5'])
fluxb = list(datatab['col8'])
I = list(datatab['col6'])
Q = list(datatab['col7'])
nr = list(datatab['col8'])
coordpair = zip(coords,nr)
loadpickle = 0
# create lists which hold the recorded values associated with an
# index number
pfluxa =[list(f) for f in zip(fluxa,range(len(fluxa)))]
pfluxb =[ list(f) for f in zip(fluxb,range(len(fluxb)))]
pQ =[list(f) for f in zip(Q,range(len(Q)))]
pI =[list(f) for f in zip(I,range(len(I)))]

# check the pointing:
plt.plot([c.ra.value for c in coords],[c.dec.value for c in coords])
plt.show()
```

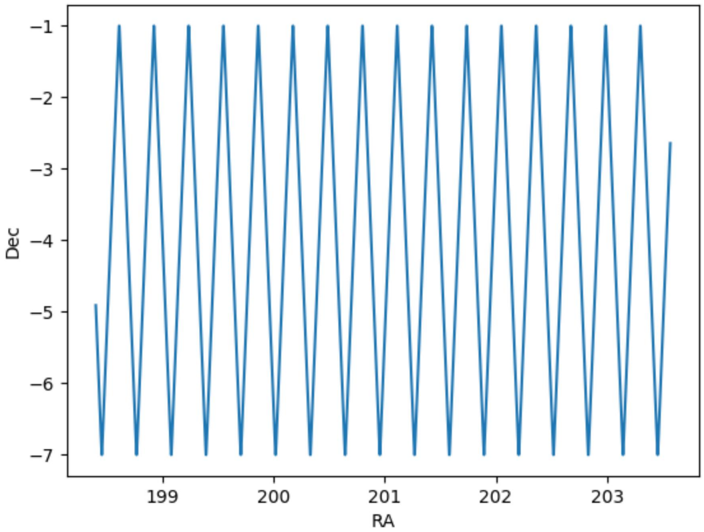

Figure 2.11

# STEP 1: check the flux vs time
# you can zoom in and look at the data
plt.plot(fluxa)
plt.xlabel("Time")
plt.ylabel("Intensity")
plt.title("Raw Data")
plt.show()

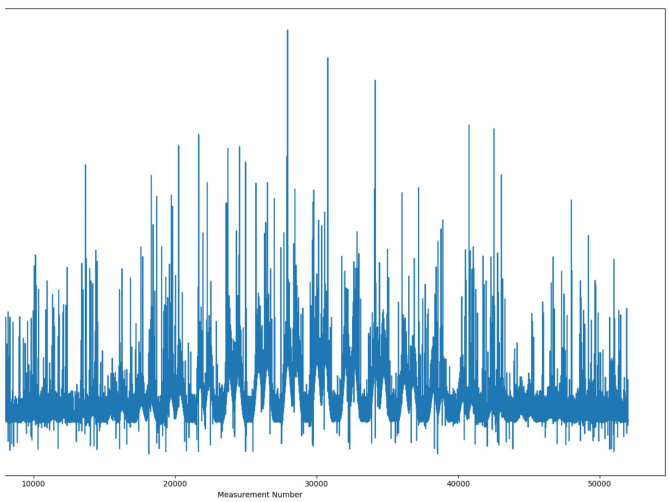

Figure 2.12

# STEP 2: noise removal
# homework: how does this noise remover work?
i=8
while i:
    ind = np.where(abs(fluxa - np.roll(fluxa,1**i)) > 60)[0]

```
    pfluxa = np.delete(pfluxa,ind,axis=0)
    fluxa = np.delete(fluxa,ind)
    print len(ind)
    ind = np.where(abs(fluxb - np.roll(fluxb,1**i)) > 60)[0]
    pfluxb = np.delete(pfluxb,ind,axis=0)
    fluxb = np.delete(fluxb,ind)
    ind =np.concatenate(( np.where(abs(Q - np.roll(Q,1**i)) > 30)[0], np.where(abs(I - np.roll(I,1**i)) > 30)[0]))
    pQ = np.delete(pQ,ind,axis=0)
    Q = np.delete(Q,ind)
    pI = np.delete(pI,ind,axis=0)
    I = np.delete(I,ind)
    i-=1

# STEP 2.5:
# after cleaning the noise, you will be asked where to start and end the data
# choose values that include the whole scan where the sun goes into the beam
# we plot the noise cleaned flux vs time data so we can decide on the data span
plt.plot(fluxa)
plt.title("Denoised Data: Decide on start and end of the data in time")
plt.xlabel("Time")
plt.ylabel("Amp")
plt.show()
```

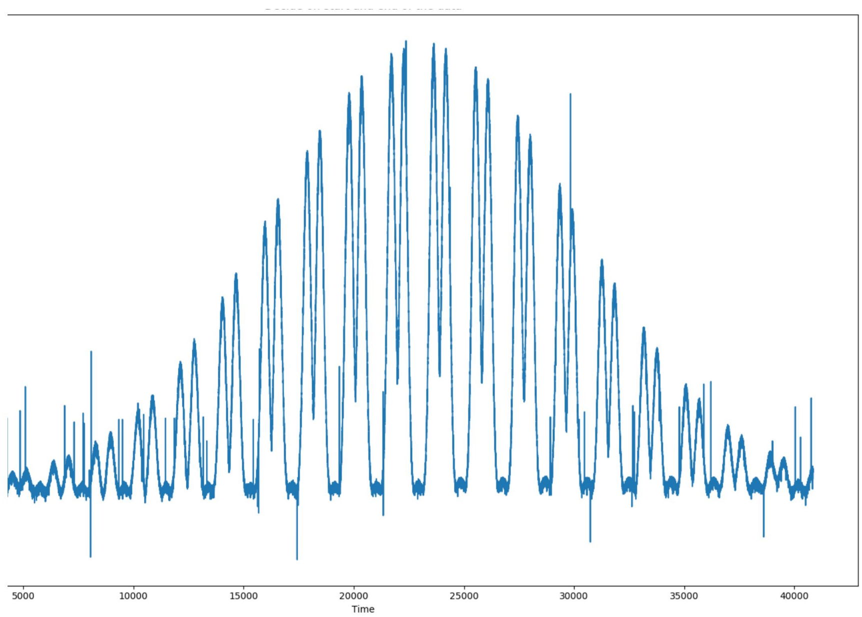

Figure 2.13