

# The 3-Meter Dish at the "Astropeiler Stockert"

## Part 1: The Setup

Wolfgang Herrmann

### 1. Why a 3-meter dish besides a 25-meter dish?

It seems somewhat strange that a 3-meter dish has been set up at our observatory even though a 25-meter dish is available which offers much more capabilities for observations [1]. There are a number of motivations why such an effort was made:

- The dish and the rotor were donated by one of the members and this created the challenge to "do something" with it.
- It was fun doing it.
- One of the aims of our observatory is to bring Physics to schools, demonstrating it by radio astronomy. We found that using the 25-meter dish is too complex in many cases for a school lab course. Therefore, a simpler setup was found to be better suited for that purpose.
- Since our 3-meter dish and the 25-meter dish have the same  $f/D$  ratio of 0.3, the smaller dish can serve as a test bed for the development of receiving horns and receiver concepts for the big dish. Feeds and front ends on the 3-m dish can be changed quickly and tested without impairing the operation of the big dish.
- Several dishes may eventually be combined to form an interferometer.

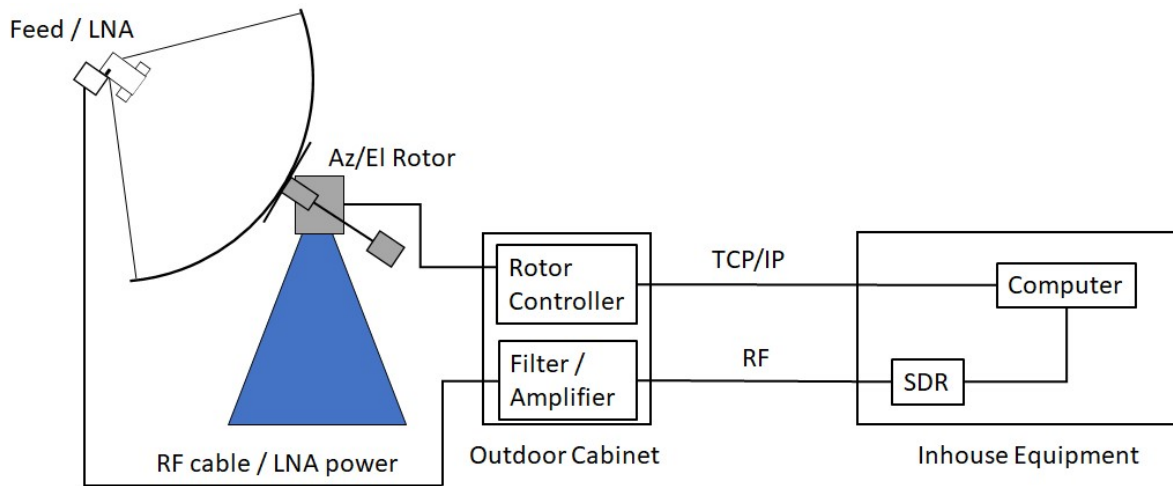
### 2. Design objectives

Observing the emission from neutral hydrogen at 1420.405 MHz was the prime objective. The intention was to provide a tool where school classes could record the spectra and determine the galactic rotation curve. In addition, continuum observations should be possible within the limits of what can be achieved with an instrument of this size. This called for both spectral resolution capability and sufficient bandwidth.

### 3. Overview of the design

The complete telescope consists of three building blocks as shown in fig. 1. They are physically separated from each other:

- The dish itself with mounting base, rotor, feed horn, and LNA
- An outdoor cabinet with rotor controller, RF filter, and line amplifiers
- Indoor equipment with a software defined radio and computer



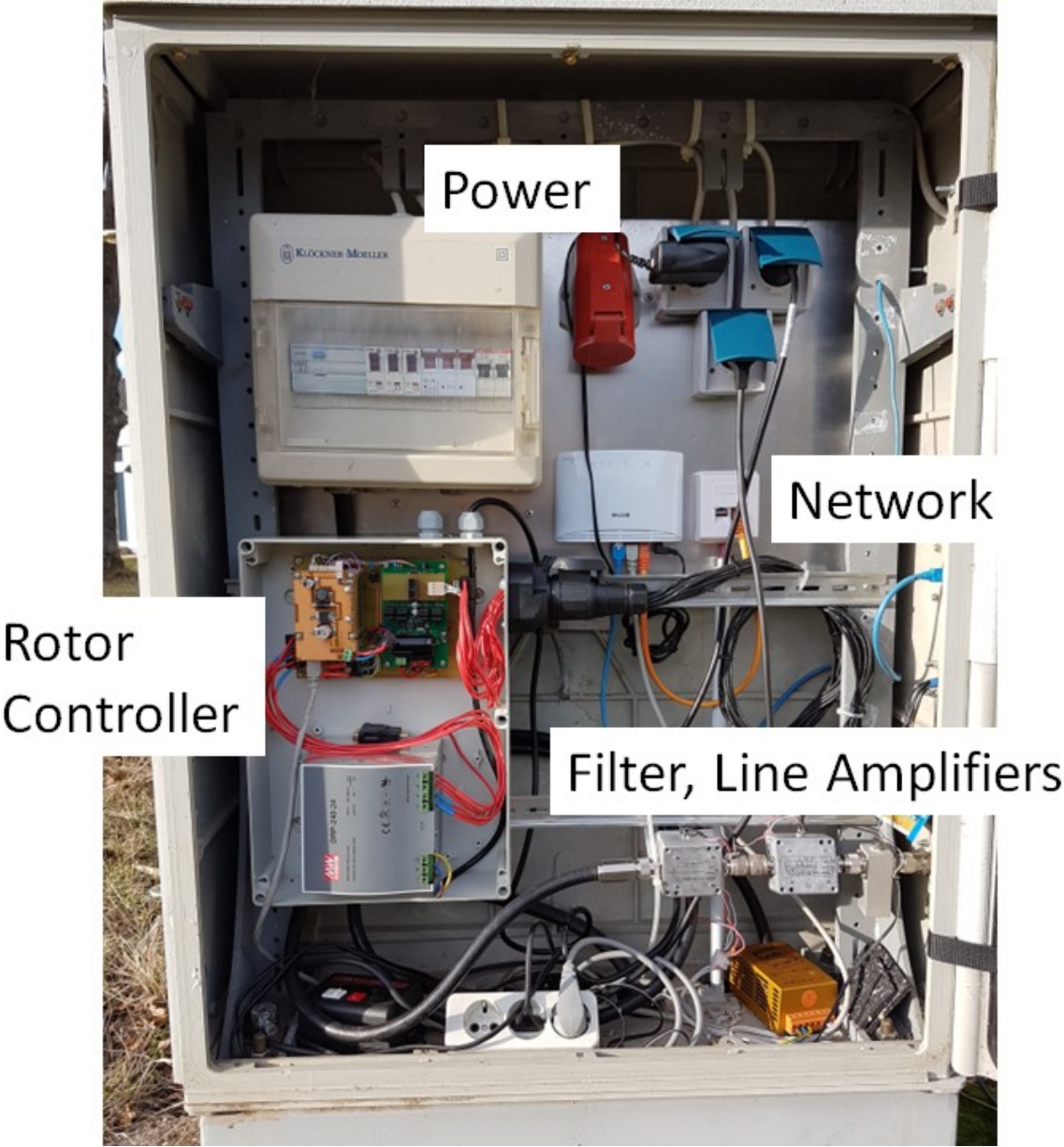
**Figure 1:** Building blocks of the telescope

The dish and the outdoor cabinet are shown in fig.2. The outdoor cabinet is a surplus cable distribution cabinet from the telephone network.



**Figure 2:** The dish and the outdoor cabinet.  
The loop antenna in between is used for other purposes and is not part of this installation

The inside of the outdoor cabinet is shown below in fig. 3.



**Figure 3:** Inside view of the outdoor cabinet

This cabinet provides power and network connectivity. It contains the rotor controller and the filter and line amplifiers. The RF signal towards the indoor equipment is carried by a low loss coaxial cable (Ecoflex 10) which is partially buried and partially laid in a cable duct.

#### 4. Mechanical setup, rotor, rotor controller

##### 4.1. Mechanical setup of the dish

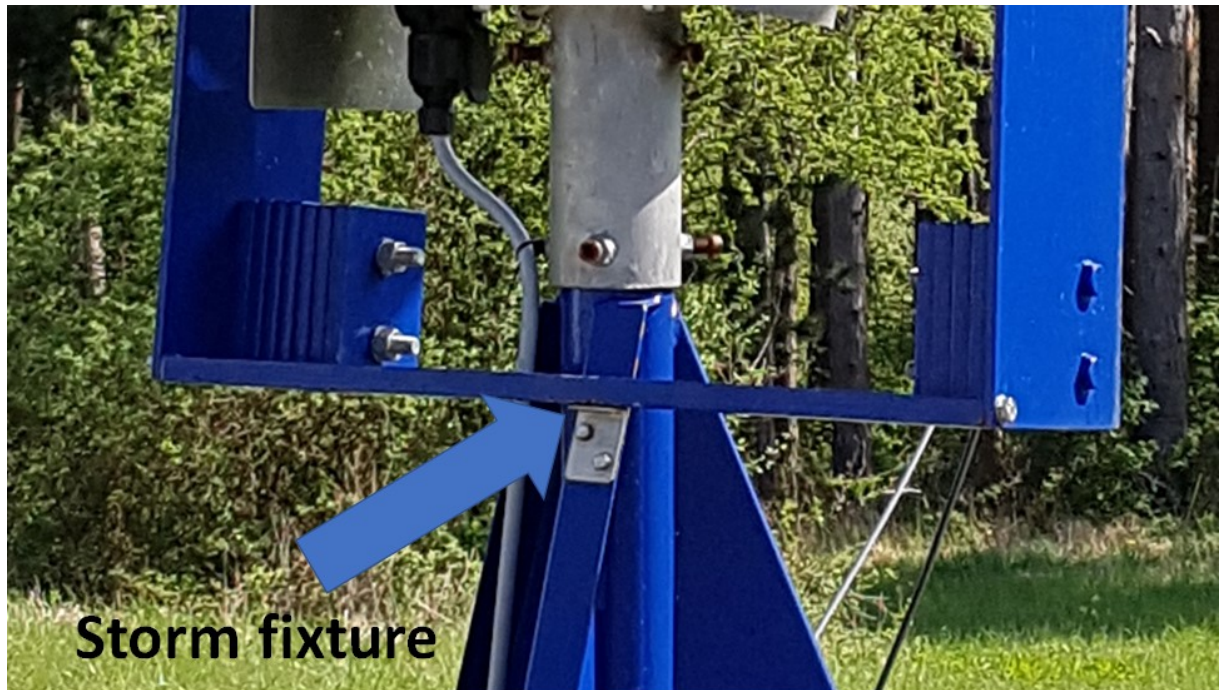
The base of the 3-meter telescope is a steel tripod which is bolted with heavy-duty dowels onto a concrete platform (fig. 4). The shape of the tripod is designed to allow full mobility over the entire elevation range without the dish or the counterweight colliding with the base. A counterweight was necessary due to the limited torque of the rotor used.

The rotor for the movement in azimuth and elevation sits on top of the steel tripod. The dish is mounted onto the rotor with an adapter plate.



*Figure 4: Overall view of the telescope*

In order to secure the dish in case of strong winds and to relieve strain from the rotor under such circumstances, a fixture was provided where the counterweight can be firmly screwed to the base, see fig. 5.

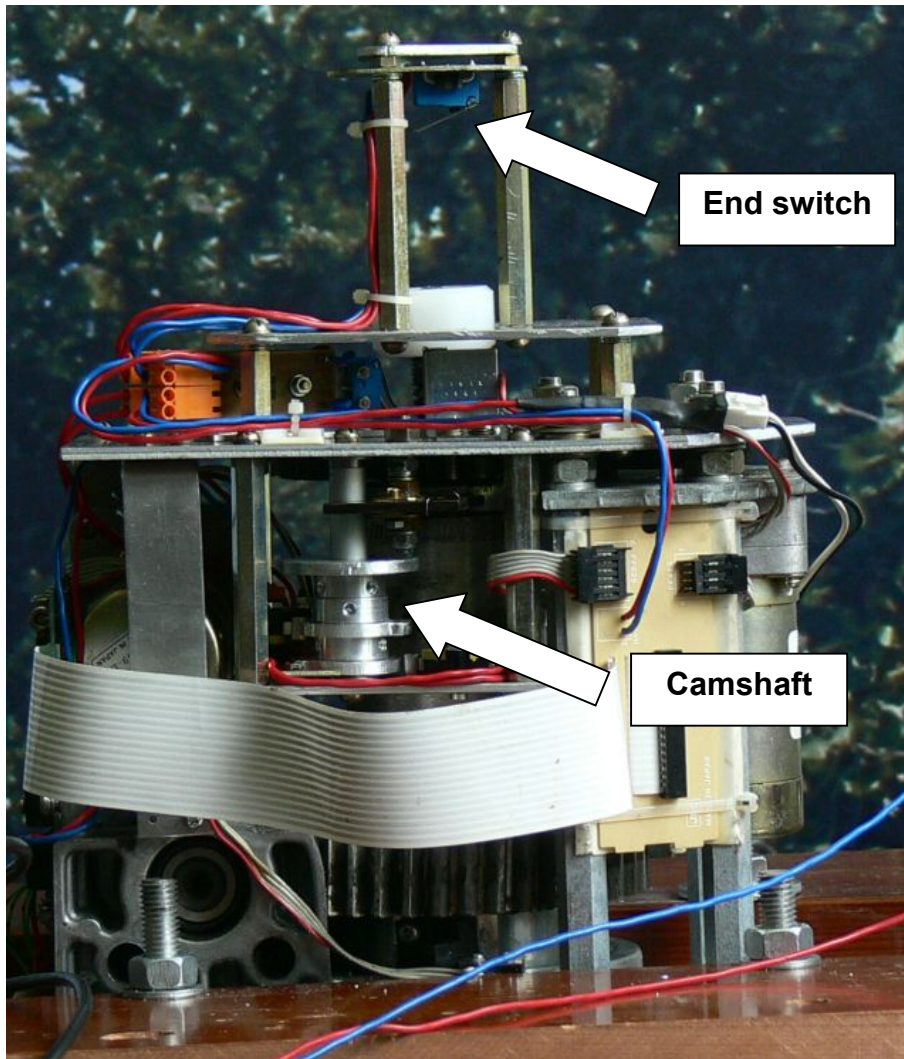


*Figure 5: Storm fixture*

#### **4.2. Rotor**

The Rotor is an EGIS ProfiTracker CL [2] with an extension kit to allow the full elevation range from 0 to 90 degrees, see fig. 10 further below.

There are a number of limitations of this unit which we had to address: There are no end switches for the elevation. We did not want to rely on the software limiting the drive range and therefore we complemented the unit with hardware end switches. These modifications are depicted in fig. 6. Likewise, the rotor can turn the azimuth indefinitely which may cause cables to the feed to be ruptured. This was also addressed by adding a camshaft to monitor rotations. Both measures required adding mechanical hardware inside the rotor housing.



**Figure 6:** Modified inner guts of the rotor

The EGIS ProfiTracker is designed to work with dishes up to 2.5 m diameter. This is further restricted by an optional kit for 90° elevation, which is specified for 1.8 m dishes. Since our dish is substantially larger we had to use a counterweight to limit the torque required. The heavier overall weight then required the replacement of some bearings. We learned this the hard way as one bearing got stuck. Another modification was to make the cable between the controller and rotor pluggable. We had chosen to use a trailer plug and receptacle which are sturdy and watertight, yet cost efficient (fig. 7).

Obviously there have been major modifications to the device in order to make it fit for our purposes. This was justified by the fact that the rotor was there and after all it was less effort compared to build something from scratch. An alternative would have been to acquire a sturdier rotor, but this would have been quite expensive.



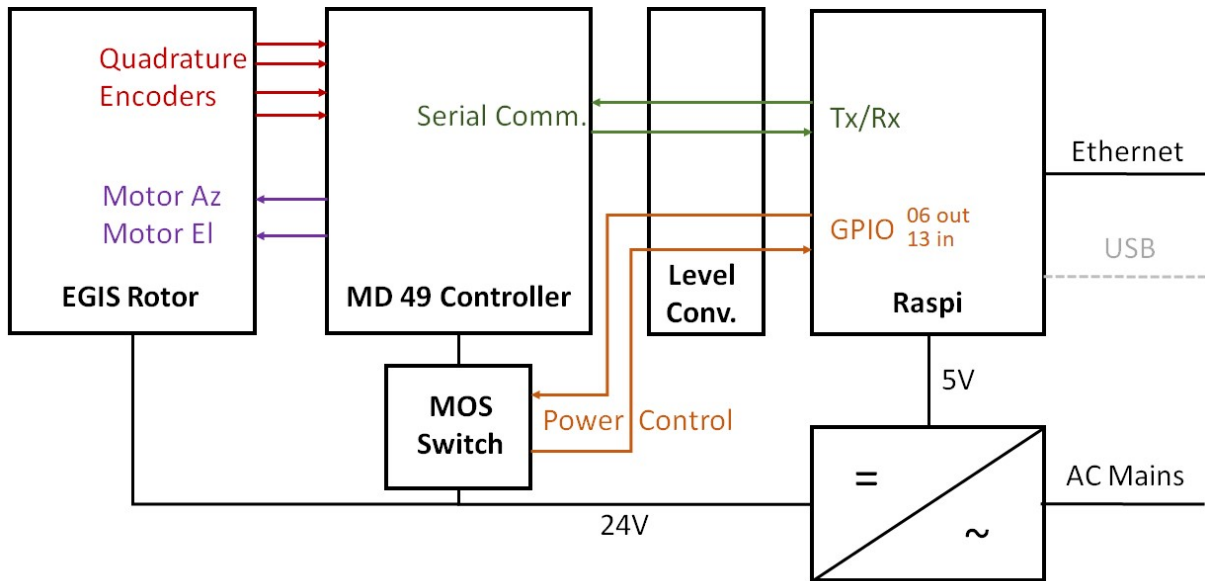
*Figure 7: Trailer plug at the rotor*

### **4.3. Rotor controller**

#### **4.3.1. Controller hardware**

The rotor comes with a controller which is primarily intended to direct a dish to various satellite positions. This is not well suited for astronomical purposes. There is a version of the controller available with a RS232 interface, however the unit we had did not have this option. Also, we wanted to have control via an IP network which would have required adaptations anyway. Therefore, the decision was taken to build our own rotor controller. This also made it very straightforward to use much of the control software used at our 25-m dish.

Our rotor controller has two main hardware components: A MD49 motor driver board made by Robot Electronics [3] and a Raspberry Pi. The MD49 motor driver provides the current to the DC motors of the rotor. It also has quadrature encoder counters which are compatible to the hall sensors of the rotor and thus allows feedback of the actual position. The communication of the MD49 with the Raspberry Pi is via a serial interface. The power to the motor controller runs through a MOS switch which is controlled by the Raspberry Pi. This allows to reset the MD49 board by the software in case an overload protection circuit of this board has tripped. A level converter is used between the Raspberry Pi and the other circuitry to adapt from 3.3 V logic to 5 V logic. A block diagram is shown below in fig. 8.



**Figure 8:** Controller hardware block diagram

The end switches for azimuth and elevation are handled completely inside the EGIS rotor without any involvement of the other devices. If an end switch is actuated, the current to the motors are interrupted. Diodes across the switches then allow that the motor can still be operated in the opposite direction so that the telescope can be released from the end switches.

#### 4.3.2. Manual operation option

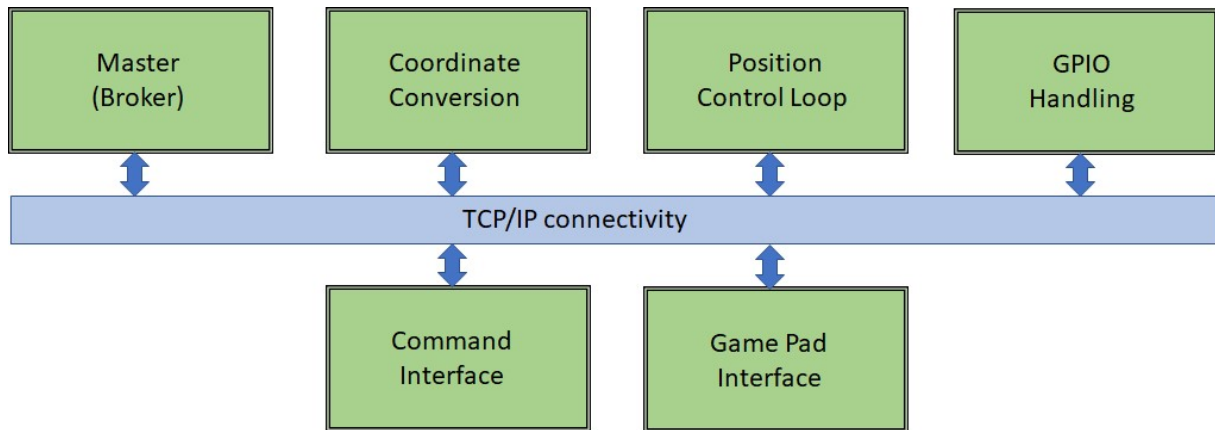
We found it convenient to have the option to manually steer the telescope when standing right beside it for maintenance purposes. This was implemented by using a wireless game controller pad. The small USB receiver of the game pad would be connected to the Raspberry Pi. The software is designed to recognize the insertion of the USB game pad receiver and then the dish can be moved using the joystick of the game pad.

#### 4.3.3. Controller software

The basic philosophy of the software design is that there is a central process which receives and disseminates information about all aspects of the telescope control. Various other processes deliver such information and/or request information. This serves two purposes: There is always a consistent picture of the overall status, and processes can be isolated from each other. Processes can also be designed to be broken up between functions which are generic and others which are specific to an individual telescope hardware. This allows the re-use of certain software components between various telescopes which is of importance for the Astropfeiler observatory. The communication between the central process and the other processes is via TCP/IP. This allows that various processes can run, if needed, on different computers. Also, the information about every aspect of the telescope becomes available all through the campus network.

The software is written in Python, making use of available modules wherever possible. An overview of the different processes implemented for the 3-m dish is shown in fig. 9 below.





**Figure 9:** Controller software block diagram

As mentioned, the master process simply maintains all information provided either as start-up configuration or through the other processes. The command interface is a text-oriented interface which interprets user input and then sets the corresponding information elements in the master process to become available throughout the system. A typical example for such a command would be a target coordinate for the telescope to go to. A coordinate conversion process takes care to continuously convert between the various coordinate systems and the machine coordinates. For example, an equatorial coordinate would be converted to other astronomical coordinates (such as galactic), to the azimuth and elevation and to the machine coordinates which are the desired encoder readings in this case. The results of this conversions are again delivered to the master. The position control loop process picks up the machine coordinates and controls the MD49 so that the desired position is tracked. The GPIO handling takes care of the direct lines to and from the Raspi such as to turn the power to the MD49 controller on and off. The game pad interface detects the presence of a pad and interprets the movements of the joystick as commands for telescope movements.

### Coordinate conversion for the elevation

The EGIS rotor creates a challenge for the control due to the mechanical design of the elevation:

A spindle moves up and down which then tilts the dish via an assembly of several hinges, see fig. 10.

This makes the elevation angle highly non-linear with respect to the vertical motion of the spindle. Even worse, the elevation becomes dependant on the azimuth: As the dish moves in azimuth, this is equivalent to turning the spindle and therefore the elevation changes.

In order to address this and get a proper relationship between the counts of the elevation encoder and the actual elevation, the elevation has been measured using an electronic inclination sensor. We took about 2200 measurement points in different azimuth directions and elevations, recording the encoder readings and actual elevation for these points.



**Figure 10:** Elevation mechanics

A mathematical model was fitted to these measurement points which then allowed to calculate the correct encoder values for all elevations and all azimuth directions. An inverse model was used to do the same calculation the other way around.

The measurement also revealed that the vertical axis was not quite vertical, it had a small tilt of 0.8° in direction of 80° azimuth. The model also allowed to compensate for this effect.

This mathematical model has been incorporated in a machine specific module in the coordinate conversion software.

## 5. Dish and Feed horn

### 5.1. Dish

The dish is an aluminium mesh dish with a diameter of 3 m. It consists of 18 segments with aluminium guides in between. The f/D ratio was determined to be 0.3.

### 5.2. Feed horn

#### 5.2.1. Feed horn design parameters

We have opted for a Kumar feed horn, also known as VE4MA horn. Details of such a horn can be found in an excellent article by Paul Wade and Tommy Henderson [4].

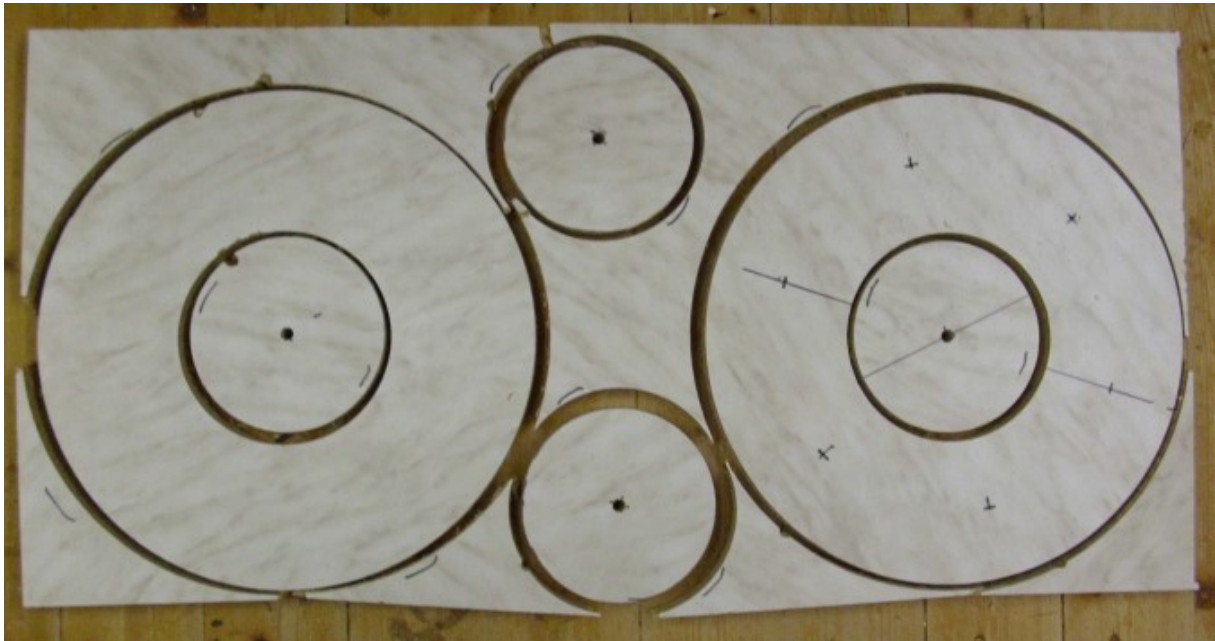
The feed horn design was done using a spreadsheet provided by the SETI league organization [5]. Parameters were chosen to bring the target frequency of 1420 MHz roughly in the middle between the TE<sub>11</sub> and TM<sub>01</sub> cutoff frequencies. The f/D ratio of 0.3 was used to calculate the choke ring position. The output of the spreadsheet with our parameters is shown below in fig. 11.

The SETI League, Inc.		Cylindrical Waveguide Feedhorn Analysis			
User specifies variables shown in		Bold			
Freq =	<b>1.42</b> GHz ;	21.1 cm	Wavelength		
Waveguide Diameter =	<b>5.45</b> in =	13.8 cm			
TE <sub>11</sub> Cutoff =	1.27 GHz ;	23.6 cm	Wavelength	Margin = 12 %	
TM <sub>01</sub> Cutoff =	1.66 GHz ;	18.1 cm	Wavelength	Margin = 14 %	
Guide Wavelength =	18.61 in =	47.3 cm			
Probe placement =	4.65 in =	11.8 cm			
Feedhorn Length =	13.96 in =	35.5 cm			
Z <sub>0</sub> =	844 ohms;	2.24	vswr		
Choke Ring Depth =	4.16 in =	10.6 cm			
Choke Ring Diameter =	13.77 in =	35.0 cm			
Dish F/D Ratio =	<b>0.3</b> (Valid range: 0.25 to 0.50)				
Feedhorn Placement: focal point of reflector falls inside lip of feedhorn by					
	0.50 in =	1.3 cm			
Choke Ring Placement: distance from front of feedhorn to back of choke ring, for					
Max. Gain (10 dB taper)	5.23 in =	13.3 cm =	0.63	Wavelengths	
Min. Noise (15 dB taper)	4.82 in =	12.2 cm =	0.58	Wavelengths	

**Figure 11:** Calculation of feed horn parameters using the SETI League spreadsheet

### 5.2.2. Feed horn practical implementation

The feed horn was hand built from sheets of galvanized steel. Wooden templates were made to give guidance when bending parts, see figs 12 and 13.



*Figure 12: Wooden templates*



*Figure 13: Bending metal using the templates*

The different parts were connected using solder as shown in fig. 14.



**Figure 14:** Choke ring soldered

The final product has a friendly face (fig. 15):



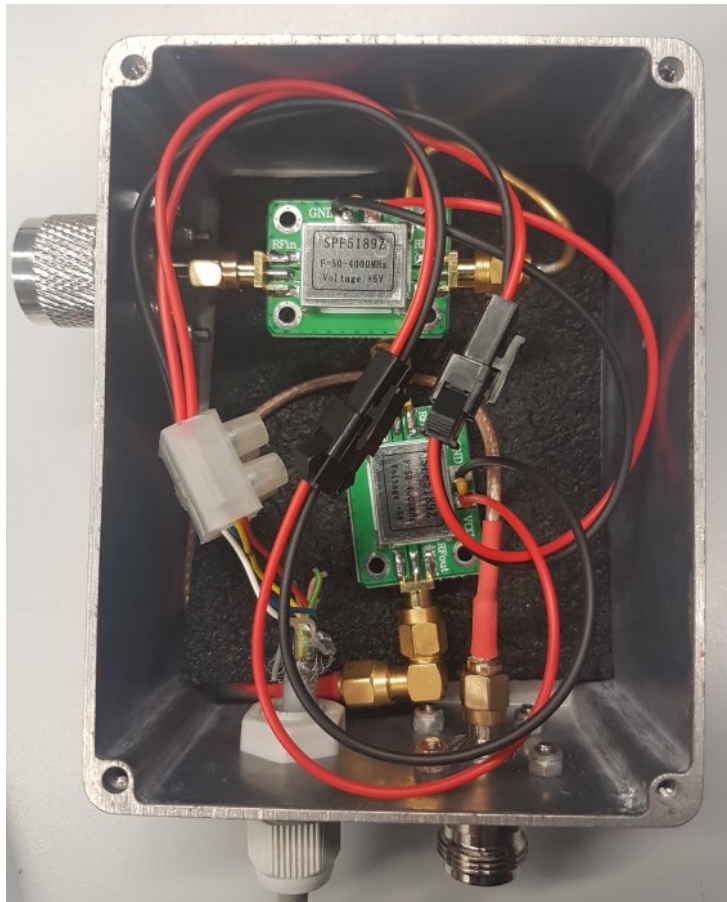
**Figure 15:** Final feed horn

### 5.3. RF-Chain: LNA, Filter, Line Amplifiers

#### 5.3.1. LNA

Different low-cost solutions for LNA's have been tested. The results of these tests have been described in the February 2019 edition of the SARA journal [6].

For the observations we have been using mostly an LNA where two devices were concatenated: A Triquint TQPM9037 as the first stage and a SPF5189Z as the second stage. Both boards were placed in a water tight aluminium die cast housing with N-Connectors. This assembly has 35 dB gain with a noise figure of 0.52 at 1420 MHz.

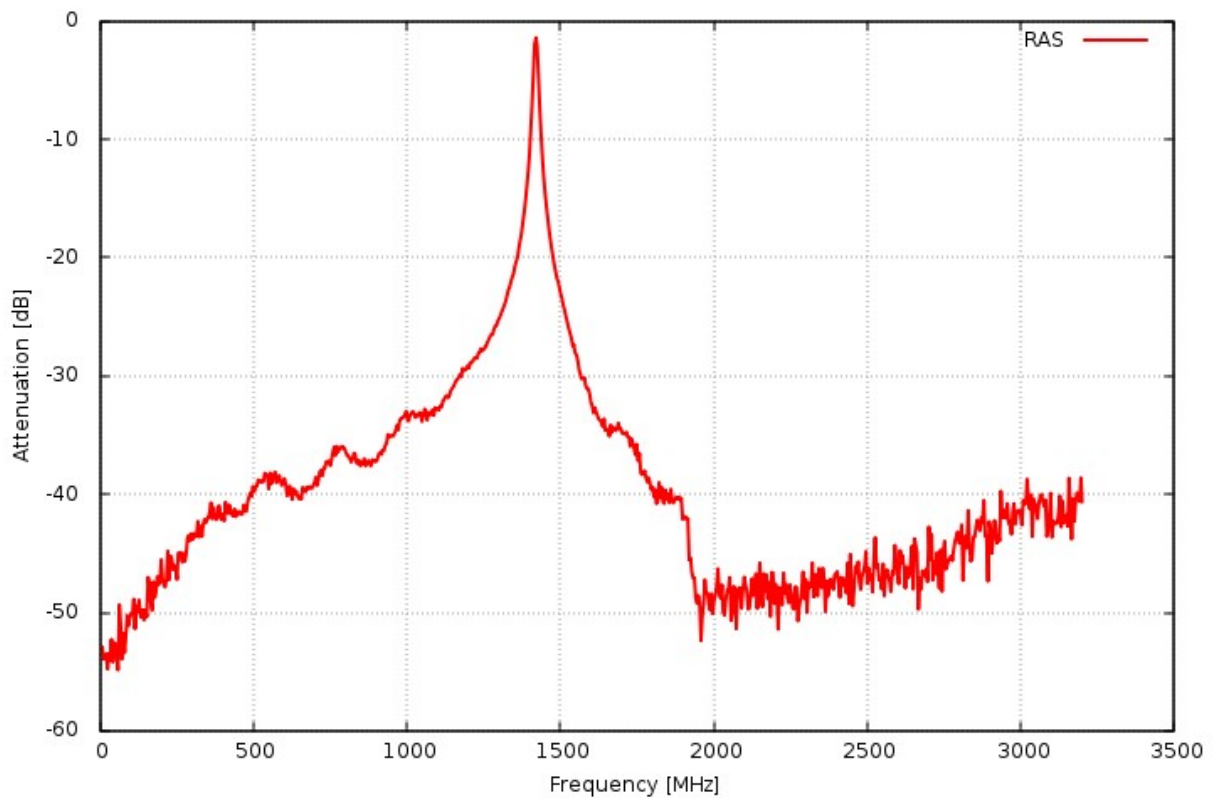


**Figure 16:** LNA setup

Fig. 16 above shows the inside of such an LNA housing. This particular unit is a version with two SPF5189Z boards.

#### 5.3.2. Filter

Various filters have been used with this telescope. These are also in the February 2019 edition of the SARA journal [6]. When doing spectral observations, most frequently we use the fairly narrow band filter from Radio Astronomy Supplies [7] offering a 3dB bandwidth of 8 MHz. The insertion loss is 1.1 dB. The filter characteristics are shown below in fig. 17.



**Figure 17:** Characteristics of the Radio Astronomy Supplies filter

However, the telescope is also used occasionally at 1612 MHz for OH maser observations. In this case, this filter is replaced by a cavity filter covering the 1612 MHz region.

### 5.3.3. Line Amplifiers

In order to compensate for the loss of the long cable run between the outdoor cabinet and the building, two line amplifiers are placed inside the cabinet. These are the amplifiers from Down East Microwave as described in [6]. They offer a combined gain of 39 dB.

## 6. Backends

Since this telescope is intended, among others, to serve as a test bench for the big telescope we have the option to set up several different backends to do comparative testing and to learn about the advantages and disadvantages of the different backend approaches. The backends are based on software defined radios (SDR). The spectral resolution required for the observation of hydrogen spectra is achieved by a Fast Fourier Transform performed on the fly on the data streams coming from the SDRs. Over time we have used various SDRs, the most important are briefly addressed below. A more comprehensive description of the various SDRs and the software used with these can be found in a previous article in the SARA journal of April 2019 [8].

### 6.1. RTL-SDR based Backend

The RTL dongle is a very popular software defined radio among the amateur radio astronomers due to its low price. This device was used for the initial tests, and “first light” was received with this backend.

## 6.2. HackRF based Backend

The HackRF is a software defined radio operating between 1 MHz and 6 GHz and provides up to 20 million samples/s. While this is more bandwidth than needed for hydrogen observations, it is convenient to have this bandwidth for continuum observations. Many of the observations done with this telescope were based on this device.

## 6.3. ADALM Pluto based Backend

The more recent observations were done with the ADALM Pluto, a device manufactured by Analog Devices. It has a higher stability compared to other SDRs which is an advantage for all observations where intensity calibration is desired.

## 6.4. Backend software

For capturing data from the various SDRs we use Soapy\_SDR [9]. This package allows to address the SDR and receive the I/Q data stream. The benefit of this package is that any higher layers of the software are isolated from the specifics of the hardware. As we want to get hydrogen spectra, a Fourier transform is performed by soapy\_power [10] which sits on top of Soapy\_SDR. A Python wrapper has been written which calls soapy\_power, captures the spectrum provided and writes this to a FITS file. The header of the file contains various information collected from the telescope control system, such target coordinates and names. The wrapper also calculates the required frequency corrections for to ensure all spectra are recorded with respect to the local standard of rest. The fits files can then be evaluated by standard astronomy packages. At our observatory, using CLASS from the GILDAS suite is the preferred solution [11].

## 7. Acknowledgements

Building this telescope has been very much a team effort. Also, we received extremely valuable support from people and organizations outside of our association. We greatly appreciate the financial support and the encouragement for this undertaking by the Rotary Club of "Euskirchen-Burgfey". One of the members of this Rotary Club is Mike Krosch who is co-owner of the company Hecker&Krosch. He and his company has made very significant contributions to the mechanical design of the instrument and assisted by manufacturing various parts, including the base and counterweight.

From our own organization many people have contributed (in alphabetical order):

- Thomas Buchsteiner, who coordinated all activities related to the overall mechanical setup and was our contact person with the company Hecker&Krosch
- Wolfgang Herrmann, who designed and built the receiving chain, migrated the astronomical software from the 25 m dish to the 3 m dish and contributed to the control software.
- Hans-Peter Löge, who built the control system hardware
- Martin Klenke, who donated the dish and the rotor
- Andreas Marschner, who designed the control system and corresponding software
- Gerhard Stramm, who built the receiving horn and who designed and built the end switch assembly for the rotor

## References:

[1] <https://astropeiler.de/beobachtungen-mit-dem-25-meter-spiegel>

[2] [http://www.egis-rotor.de/aroto\\_us.html](http://www.egis-rotor.de/aroto_us.html)

[3] <https://www.robot-electronics.co.uk/products/drive-systems/motor-boards/md49-24v-5a-dual-h-bridge-motor-driver.html>

[4] [www.w1ghz.org/antbook/conf/high\\_efficiency\\_prime\\_feeds.pdf](http://www.w1ghz.org/antbook/conf/high_efficiency_prime_feeds.pdf)

[5] <http://www.setileague.org/software/feedhorn.xls>

[6] [https://astropeiler.de/sites/default/files/Hydrogen\\_2.pdf](https://astropeiler.de/sites/default/files/Hydrogen_2.pdf)

[7] <https://www.radioastronomysupplies.com/>

[8] W. Herrmann, Hydrogen line observation: From frugal to advanced, Part 3, SARA Journal, April 2019

[9] <https://github.com/pothosware/SoapySDR/wiki>

[10] [https://github.com/xmikos/soapy\\_power](https://github.com/xmikos/soapy_power)

[11] <https://www.iram.fr/IRAMFR/GILDAS/>