A Transportable Radio Telescope for School Projects

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1. Introduction

Bringing Physics to schools by means of radio astronomy has always been one of the targets of the “Astropeiler Stockert e.V.” This association of volunteers operates a large radio astronomy facility in Germany. This observatory encompasses a 25-m dish, a 10-m dish, a 3-m dish and a Ku-band interferometer. These instruments offer a large variety of possibilities to do lab courses with school classes. However, it is not always possible for schools to organize travelling to the observatory site and spend time there. Therefore, the idea came up whether it would be possible to build a small telescope which can be brought to schools and to do experiments there.

It has been demonstrated that the observation of the hydrogen emission at 21-cm wavelength can be done with very minimal size antennas [1].
Therefore, it seemed to be possible that a dish small enough to be transportable would be sufficient to do observations of the hydrogen emission and derive, among other experiments, the rotation curve of the milky way.
In this article we describe the setup, the operation and observational results of such a small telescope.

2. Design targets and basic concept

The design target for this telescope has been:

- Allow the observation of the 21-cm emission of neutral hydrogen
- Be easily transportable with only minimal effort to set up
- Be fully self-contained with all hardware and software components ready for operation
- Require only minimal cabling on site
- Come with comprehensive instructions on how to use and what experiments to do
- Re-use as much as possible existing hardware and software developed for the other telescopes

A dish of 1.2 meter diameter has been chosen for ease of transportation. As the observation of the galactic plane should be possible within the timeframe of a short course, this dish needed to be steerable in azimuth and elevation so that a full scan could be done within limited time. We had chosen to use the same rotor as for our 3-m dish so that we could re-use controller hardware and software [2]. In order to be easily transportable, the whole telescope was be mounted on a trailer. The telescope assembly on the trailer was designed to include the hardware for the rotor and also the complete RF part. This allows that only a power and a network connection are needed for the operation. A laptop is connected via this network connection for processing and display of results.

3. Setup

The telescope is shown in fig.1 in its operating configuration. A frame from aluminium profiles forms the base of the telescope. This frame is firmly fixed on the trailer. The rotor sits on top of the frame and allows mobility over the full azimuth and elevation range. For transportation, the dish is taken off the rotor in order to minimize wind resistance (fig 2.)

Figure 1: *Telescope ready to operate*

Figure 2: *Telescope in transport configuration*

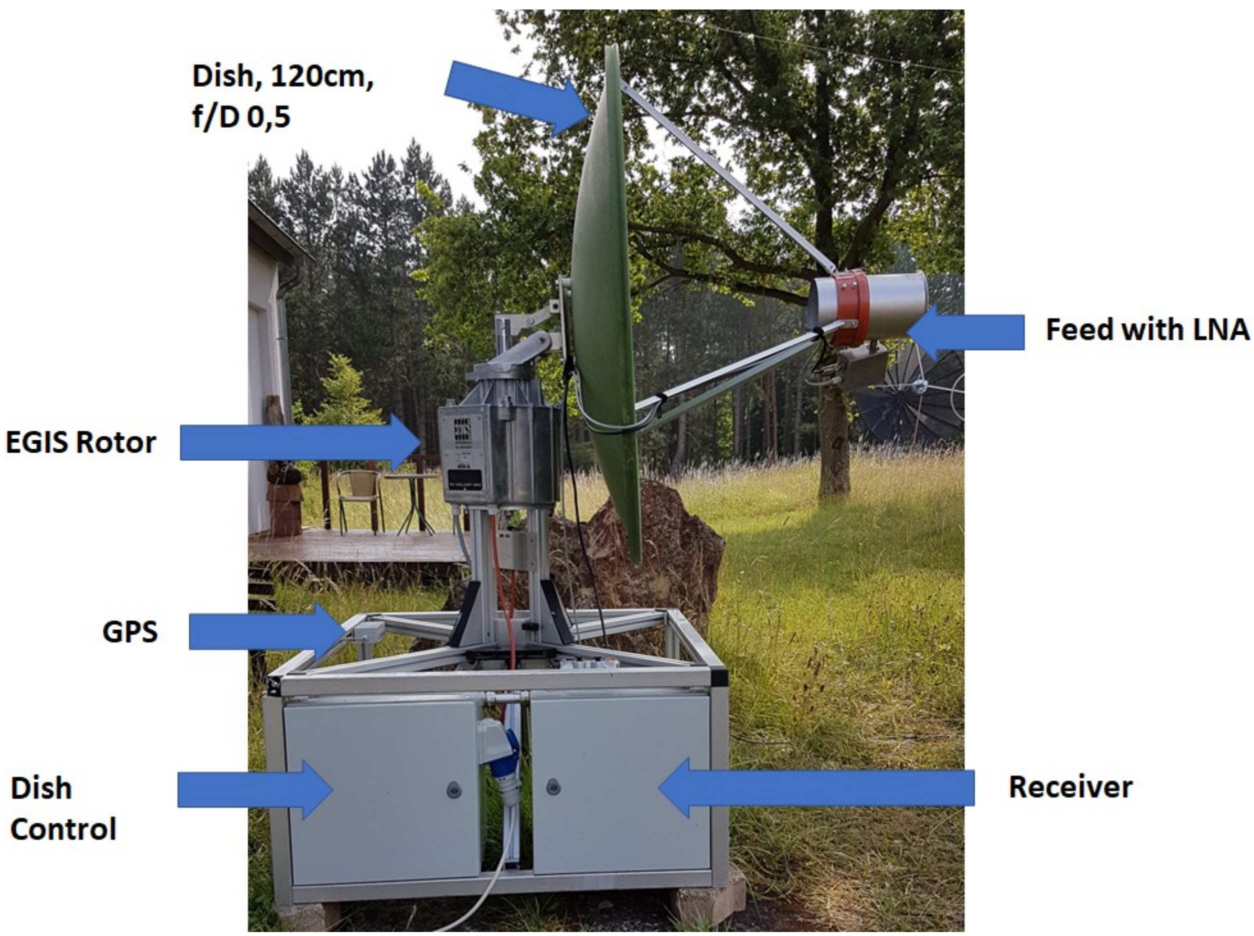

Figure 3: *Telescope unit without trailer*

Fig. 3 shows the telescope unit and its main components without the trailer. Beside the dish itself, there is the feed horn with low noise amplifier (LNA), the rotor, a GPS receiver and two metal enclosures. The GPS receiver provides the position and time to the control system. The control system itself is mounted in the left metal enclosure. The right enclosure contains a RF-filter and the receiver which is based on a software defined radio (SDR).

3.1. Dish and feed horn

The dish has a diameter of 120 cm and a focal length of 60 cm. This is a fairly flat dish with a f/D ration of 0.5. The feed horn is a simple circular waveguide which was made from a stove pipe with 15 cm diameter. The beam profile of this feed horn has been measured as shown in fig. 4. The blue arrows denote the direction towards the rim of the dish. It can be seen from this diagram that the illumination of the dish is quite satisfactory. However, there is also a significant overspill so that a higher system temperature can be expected. This is a compromise which has to be accepted with a simple horn like this.

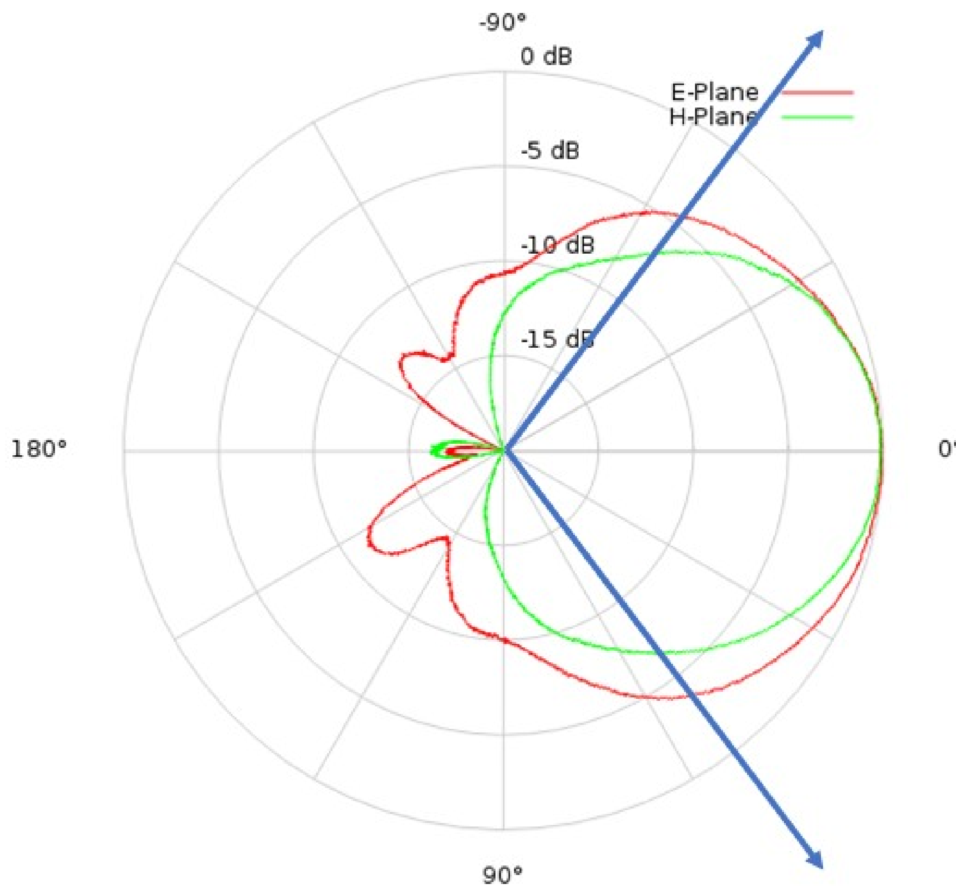

Figure 4: *Feed horn beam profile*

3.2. LNA

The low noise amplifier consists of two modules with a SPF5189Z P-HEMT transistor. Such modules can be bought quite cheaply and offer an acceptable noise figure. This LNA configuration provided a gain of 27 dB at a noise figure of 0.88 dB.
The modules are mounted in a watertight Aluminum die cast housing which is equipped with N-connectors. Power supply is provided by a separate cable from the receiver unit. This LNA design is the same as described in [3].

3.3. Receiver unit

The LNA is connected with the receiver unit via a coaxial cable with N-connectors. This receiver unit consists of a cavity filter and an ADALM-Pluto software defined radio. The filter has an attenuation of 0.4 dB at 1420 MHz and a 3 dB bandwidth of 24 MHz. This filter follows the design by Matjaž Vidmar as described in [3]. The SDR is equipped with an USB to Ethernet adapter. This adapter was used so that a separate laptop can be set up distant from the telescope and be connected via network, see section 4. for more details. All parts of the receiver unit are mounted inside the right metal enclosure. A view of the inside is shown in fig. 5.

Figure 5: *Receiver unit*

3.4. **Control unit**

The left metal cabinet contains the control hardware, power supplies and a Gigabit-Ethernet switch. Connections to the rotor, the network and to power all use watertight connectors. In order to make an USB port available from the outside, a waterproof USB socket is mounted at the cabinet. A view of the inside of this unit is shown in fig. 6.

The control hardware consists of two main elements: A MD49 motor controller board from Robot Electronics [4] and a Raspberry Pi. The motor controller board delivers the drive current to the motors for azimuth and elevation. This board also contains counters for quadrature encoders which are compatible with the sensors in the rotor. This is used to get feedback for the azimuth position. Communication between the MD49 board and the Raspberry Pi is via a serial interface. Power to the motor controller is provided via a MOS switch. This allows that the motor controller board can be reset via the Raspberry in case an overcurrent protection circuit has tripped. Conversion between the 5V logic of the controller and the 3.3 V logic of the Raspberry is done via separate converters.

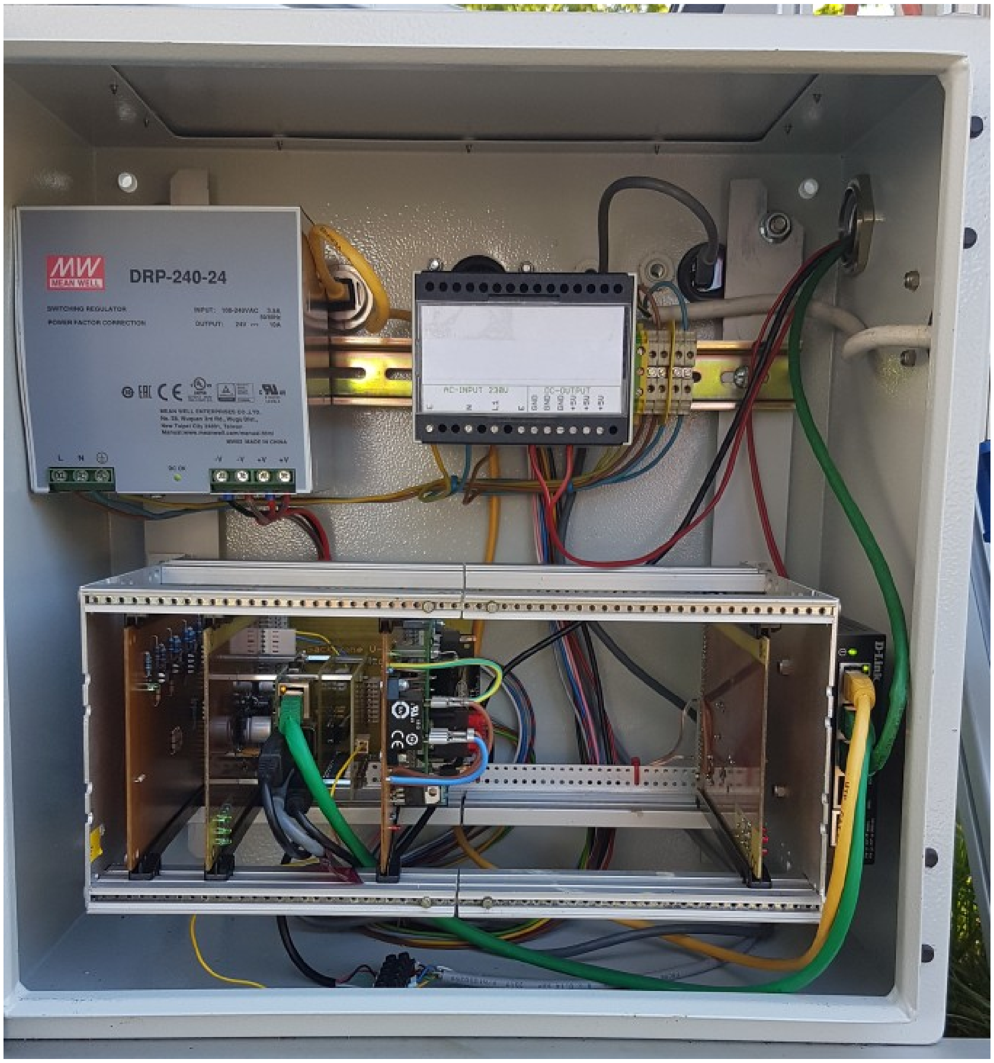

Figure 6: *Control unit*

In order to control the elevation, an inclination sensor is used. This was chosen rather than using the internal coders of the rotor as it is not certain that the trailer will always be standing level. The inclination sensor is an ADXL 203 from Analog Devices. It is connected to an Arduino Nano. This Arduino calculates the inclination from the sensors raw data and transmits it to the Raspberry Pi via an USB connection. Another USB connection is used to connect a GPS module. Accurate position and time are made available through this. Timing accuracy is enhanced by evaluating the PPS pulse from the GPS (even though this may be a bit over the top for a telescope with a wide beam width).
A block diagram of the unit is shown in fig. 7,

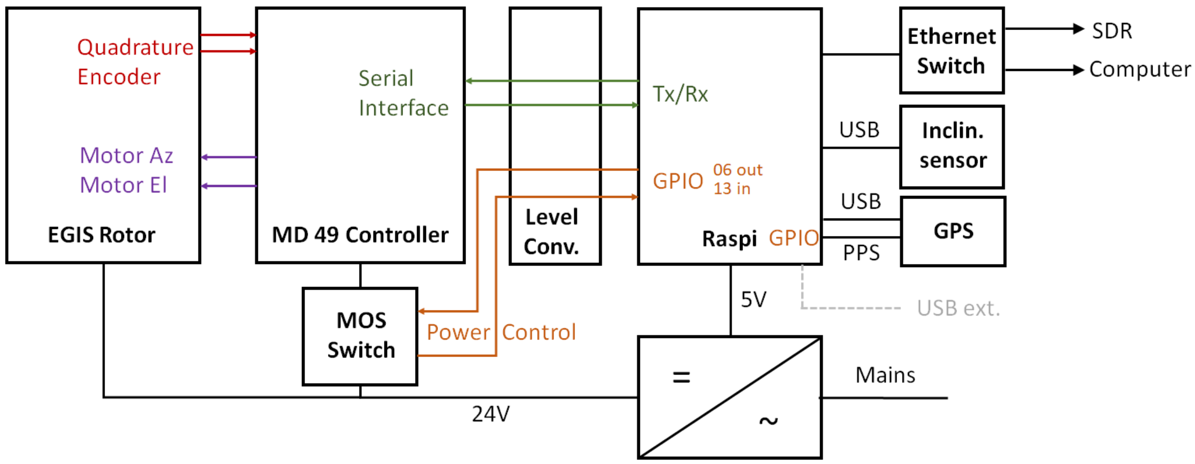

Figure 7: *Control unit hardware block diagram*

The external USB port is used in particular to connect a game controller. This allows to manually control the telescope via a joystick. This is used for initial alignment. Inserting such a controller is automatically detected and the corresponding function is then activated.

3.4.1. **Control software**

To a large extent, the control software is identical to the software used for our 3-m dish at Astropeiler. This has been described in [5]. The basic philosophy of this software is that a central process administers all information provided by various modules and disseminates this information back to the processes. This assures that a consistent status is available about all instrument functions. This also allows to separate generic from telescope specific functions which facilitates re-use of existing modules. Inter-process communication is done via TCP/IP. The software has been developed using Python. Wherever possible, existing packages have been used. An overview of the different processes which are used for this telescope is shown in fig. 8.

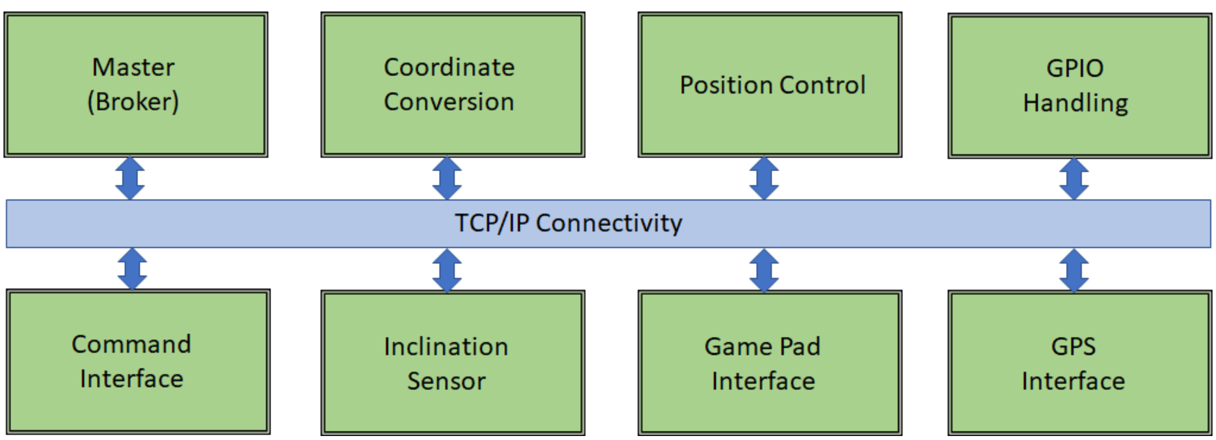

Figure 8: *Software Modules*

4. **Software for observations, data acquisition and data representation**

The software which provides the user interface to the telescope control and the software to collect and process the data runs on a laptop which is connected to the telescope. The connection is made via the ethernet switch which is part of the telescope.

4.1. Command interface

The command interface is text oriented. It runs on the laptop and communicates with the Master process in the telescope. Alternatively, the command interface can also run on the Raspberry Pi in the telescope which is useful for maintenance purposes.
The command interface allows to provide target coordinates in equatorial and galactical format as well as direct azimuth and elevation. Also, a number of selected targets is available by using their name. Other basic functions like turning on and off, showing the actual position and the tracking status are supported by this interface.

4.2. Signal processing and display

The SDR in the receiver section of the telescope delivers the received signal in the form of complex values (I/Q-data). This data represents the magnitude and the phase of the received signal. Depending on the bandwidth required, the data rate between the SDR and the processing laptop can be up to 200 MBit/s. This incoming signal is continuously processed by a Fast Fourier Transform (FFT) algorithm.
For controlling the SDR we are using a program system called SoapySDR [6] together with soapy_power [7] for the FFT. Both packages are freeware. The layer above these consists of three different programs which are our own development and are written in Python:

- A program, which represents the total power as the sum of all spectral channels and displays this live or records it (continuum signal)
- A program which receives the spectrally resolved data once per second, performs a baseline correction and displays the result in a live window
- A program, which records the data with a defined spectral resolution and a defined integration time and writes the data into a file in the Flexibile Image Transfer System (FITS) format for later analysis.

The first two programs are primarily intended for school lab courses. The third program is intended for advanced experiments, where the rotation curve of our galaxy is determined. All programs are designed to show spectra and velocities corrected for the local stand of rest (LSR). This is a reference frame where the motion of the earth is calculated and the data is corrected, so that the measured results become independent on the time and location of the measurement.

An example how the live display from the first program looks like, is shown below in fig. 9. This is updated every second so that a continuous profile is created. The momentary value is shown in addition as a number. In this example the telescope was moved towards the sun and then moved again away from the sun. A significant increase in continuum radiation due to the sun is obvious.

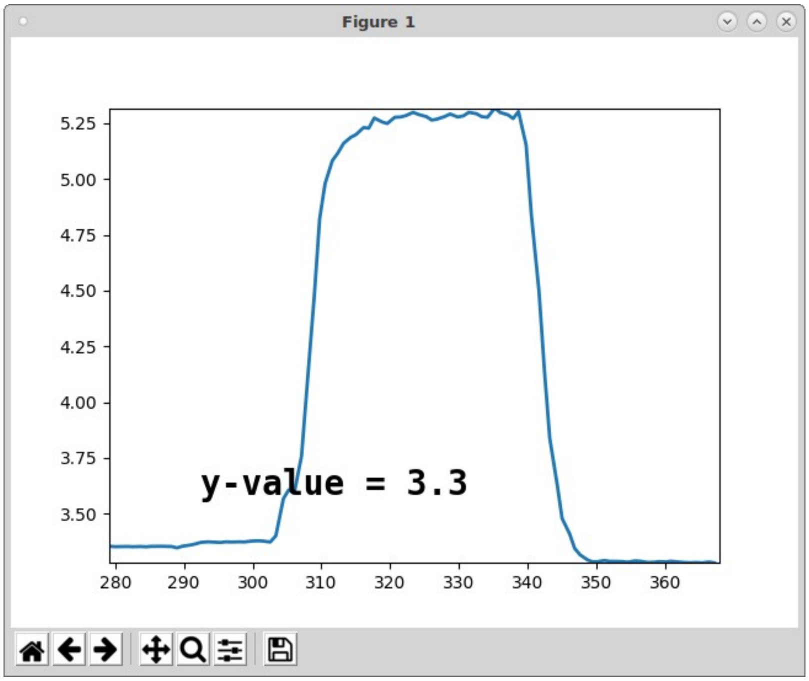

Figure 9: *Continuum signal from the sun*

The second program for the live display of the spectrum creates a plot like shown in fig. 10. This example demonstrates the spectrum towards a galactic longitude of 90° in the galactic plane (gal. latitude 0°),
The narrow line at around 200 km/s is RFI and not of astronomical origin. The intensity in not calibrated in this example. The benefit of this display especially for school programs is that the change in the spectrum can immediately be observed when moving the telescope to different parts of the sky.

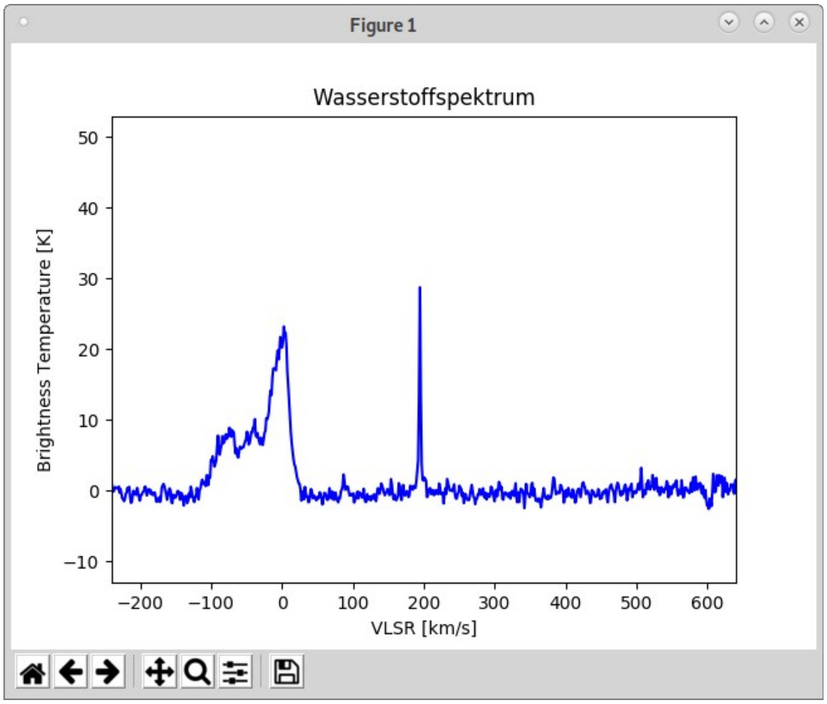

Figure 10: *Live display of the spectrum*

The next example shown in fig. 11 is a spectrum recorded with the third program mentioned above. The FITS file generated by this program was processed with CLASS, which is part of the GILDAS package [8]. The spectrum is from the same location as in the previous example, i.e. galactic longitude 90° and galactic latitude 0°. The integration time was one minute, using a spectral resolution of 1.47 kHz per channel. The two narrow spikes at around -75 km/s and 95 km/s are RFI which do not belong to the hydrogen spectrum.

Even though the spectral resolution is higher compared to the live picture, the signal to noise ratio is better due to the longer integration time.

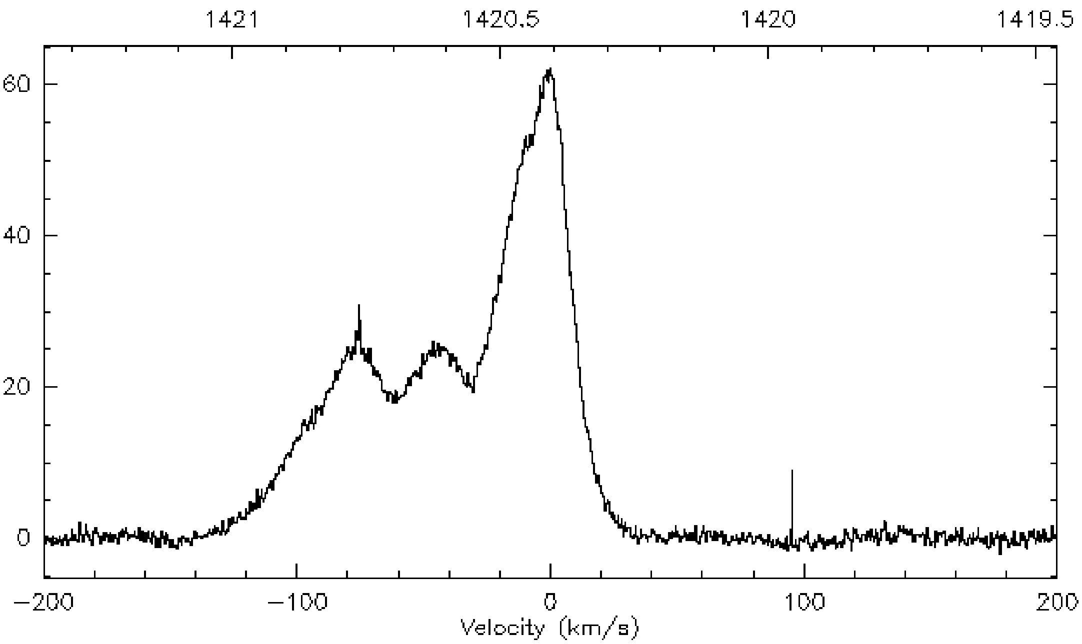

Figure 11: *Observed spectrum towards longitude l=90°, latitude 0°*
Vertical scale is brightness temperature in K
Lower horizontal scale is velocity in the LSR rest frame
Upper horizontal scale is frequency in MHz

5. **School program and pedagogical concept**

Radio astronomy is not part of the syllabus of schools, and even general astronomy is dealt with only on a very generic level. Therefore, it was necessary to develop a program including material for teachers and students which introduces the general concepts and physics of radio astronomy and to give detailed instructions on how to perform experiments and evaluate them.
Developing such a program and material requires a good understanding on how to bring this across to both teachers and students. It had to be designed as an overall pedagogical concept. This whole package was developed as a Master Thesis by Felix Stöhr [9] who was finalizing his studies to become a physics teacher. The first part of the package describes all theoretical background needed:

- Basic information about radio astronomy in general
- History of radio astronomy
- 21-cm line and its origin
- Astronomical coordinates
- Doppler shift
- Basic setup of a radio telescope

The second part of the package contains the experiments with detailed instructions on how to perform them:

- Shape of the milky way
  The hydrogen line is observed when the telescope is first directed to the galactic plane and then outside the galactic plane (in steps of 5° of galactic latitude in both directions). The students will notice that the signal decreases when moving outside the galactic plane. They will learn that this is an indication that the milky way is a flat disk.
- Heat and radio emission
  The students will observe the continuum signal as it rises if someone puts his hands in front of the receiving horn. Other materials will be tried as well to see their impact. They will learn that any warm object emits radio waves and that the sky itself is cold.
- Determine the system temperature
  The students will direct the telescope to a cold position in the sky (celestial pole) and to an absorbing object such as trees. They will record the difference in intensity. Using the Y-Factor method they will determine the system temperature of the telescope.
- Rotation curve of the milky way
  The students will measure the velocity of the hydrogen clouds in different directions in the galactic plane. They will learn how to interpret the results to obtain the rotation velocity as a function of distance from the galactic center. They will learn that the result is not what one would expect from Kepler's law based on the distribution of visible masses. They will learn that today's astronomers explain this by the existence of dark matter.

The teacher will decide which and how many of these experiments are suited for his/her students so that the program can be tailored based on the age and pre-knowledge. A test run of these experiments had been performed with one school in order to learn from that experience and fine-tune the educational material.

6. Conclusions

A small radio telescope with only 1.2-m dish diameter is fully sufficient to allow a number of experiments which can introduce students from schools into the basics of radio astronomy. It can be designed to be easily transportable to a school campus. Quick and easy setup on site can be achieved by placing all components within the transportable unit.

7. The Team

As usual in our organization, designing and building this telescope has been a team effort. Many have contributed, and this list may not even be complete. But here are the main contributors in alphabetical order:

Thomas Buchsteiner: Integration of all hardware components
Bert Engelskirchen: Feed support and various mechanical parts
Hans-Peter Löge: Control hardware and parts of the control software
Wolfgang Herrmann: Concept, RF-design, LNA, software, system integration
Karl-Josef Mauel: Acquisition and licensing of the trailer, transport fixtures
Felix Stöhr: Pedagogical concept (Master Thesis)

Gerhard Stramm: Cavity filter

8. Acknowledgements

We appreciate the donation of the dish by Per Dudek, Kiel and the donation of the Aluminium base structure by the Max-Planck Institute for Radio Astronomy. We gratefully acknowledge the manufacturing of new enhanced bearings for the rotor by the company Hecker&Krosch. We appreciate that the University of Bonn has granted a Master Thesis to Felix Stöhr to develop the pedagogical concept.

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