

Low cost equipment to observe neutral hydrogen at wavelength 21cm

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The goal of this project was to demonstrate how to setup and operate a low cost instrument to observe neutral hydrogen at 21cm wavelength. The project was started 12 years ago together with students of ETH Zurich, Institute of Astronomy. At those time is was quite difficult to get components for such an instrument and sub-system like low noise amplifier (LNA), receiver (RX) and spectrometer were super expensive. Here I'll demonstrate that a working system can be setup for less than a few 100\$.



Fig. 1: Old, used parabolic dish from flea-market which I got for 100\$ several years ago. Unfortunately, I don't have access to a mounting- and tracking-system. Therefore the dish was put on a garden table and tilted with some wooden blocks underneath, such that the antenna beam is pointing to a dedicated position on the sky.

I prefer a dish with central feed such one can 'see' where the antenna is looking to. In principle one can also use an offset dish from satellite television. But it looks odd and one can hardly find out where the offset-antenna is pointing to. Pointing calibration with central feed dish can easily checked while pointing to the Sun and observing the shadow of the feed in the center of the dish. This is difficult in case of an offset dish.

Observation of neutral hydrogen in our galaxy (Milky Way) is a nice experiment which works all day long, day and night. Even during rainfall, snowfall and clouds we can perform observations while optical observations are impossible. Therefore this experiment has been selected as a 'emergency' one in case of bad weather conditions.

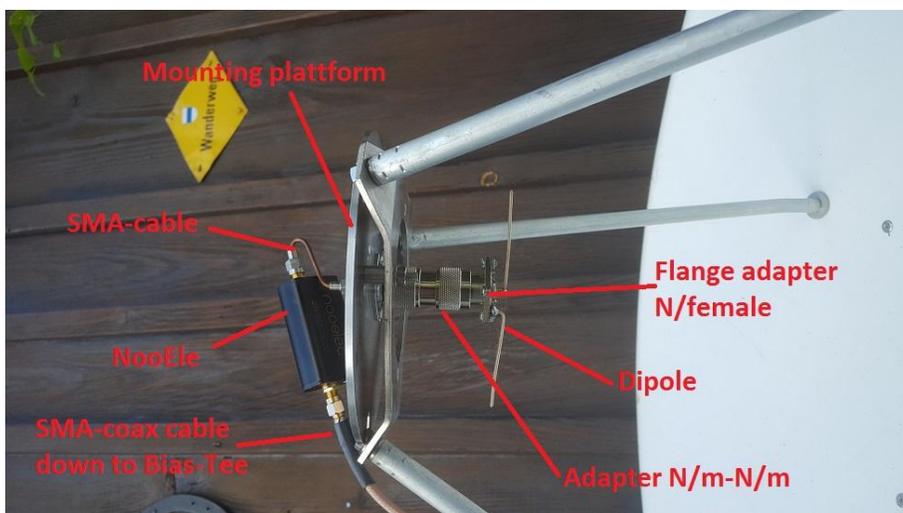


Fig. 2: Here we can see the so-called frontend, composed of antenna-feed (dipole), mounting platform, band-pass-filter and low noise amplifier in form of the NooElec unit. Dipole and amplifier are mounted on a small platform close to the focal plane of the dish. Using connectors and adapters we put the dipole exactly at the focal plane of the dish.

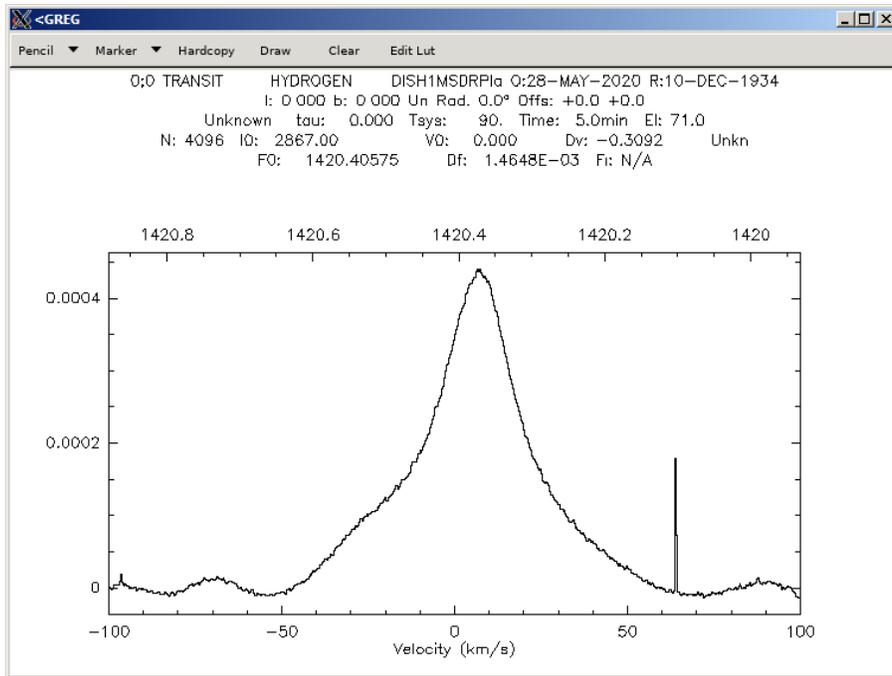


Fig. 3: Single spectrum, taken with the described setup. Part of the software which runs on the Raspberry Pi is CLASS, a professional software tool to handle spectra. This includes reading files, plotting, zooming, smoothing, subtracting background and many other functionalities required to produce 'nice' plots. Peak around 63km/sec is due to local interference (rfi).

Beside the telescope with the so-called frontend we also need a backend which is composed of a receiver, usually kind of SDR (software defined radio) and a computer, in this case a Raspberry Pi with 4 GB memory to read data from receiver and to perform fast Fourier transformation (FFT).

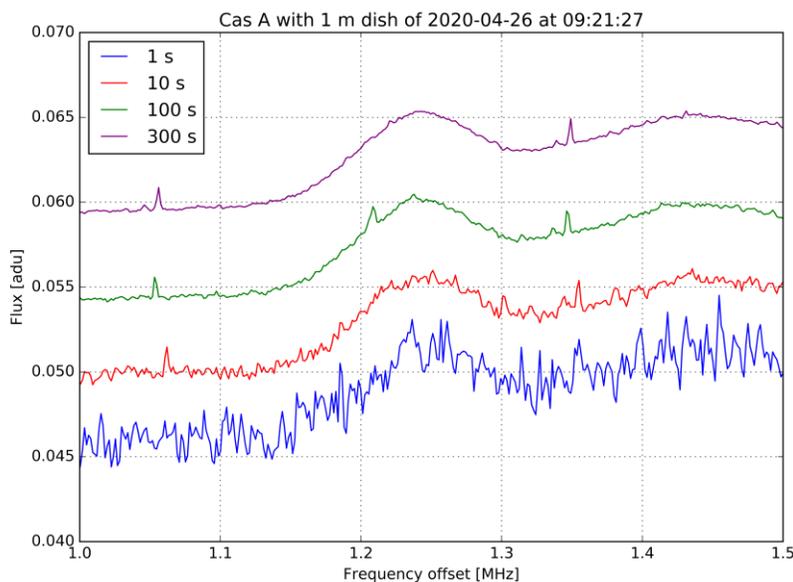


Fig. 4: Plot left demonstrates the effect of integration time. The longer we integrate, the smoother the plots look like. If we integrate 16 times longer the signal to noise ratio (SNR) improves by square root of 16, in this case four times better. Measuring 1 seconds we can already see the spectral line, but to get really good quality I need to integrate for at least 100 seconds. On the other hand one should not integrate too long because during longer time the sky moves out of the beam and the risk to collect rfi is increasing. For each setup there is an optimum integration which you need to find out.

One of the simplest experiments beside observing just a single spectrum is to map part of the Milky Way. In my case I position the telescope in such a way that the sources of neutral hydrogen move through the antenna beam. We call this observation mode transit observation. A special case is called transit meridian in case the dish is exactly looking to south direction. When we observe for 24 hours as demonstrated in figure 6, we see two spots of neutral hydrogen as indicated in the map on figure 5. Here the telescope was positioned at azimuth 170° and elevation 71° such that Cygnus region will be part of the observation.

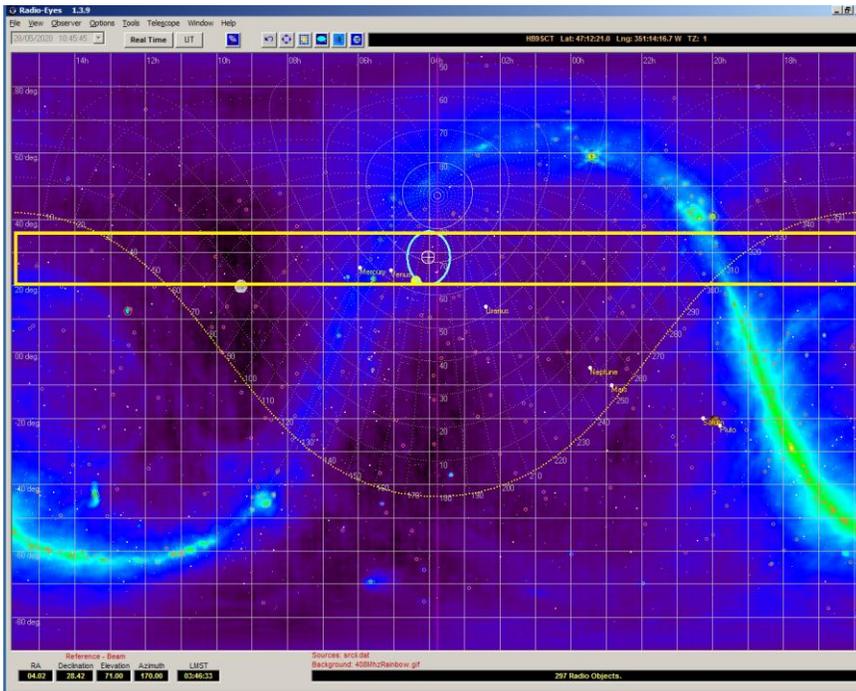


Fig. 5: Planning tool Radio Eyes from Jim Sky is very helpful in positioning the antenna to observe dedicated positions on the sky. In this case with fixed azimuth and fixed elevation we map a stripe on the sky (between yellow lines) producing two spectra within 24 hours of observation. Depending on location where the telescope is installed we even need to position the telescope slightly north to observe Cassiopeia A and calibrations source S7.

The backend composed of receiver and computer can be operated locally with mouse, keyboard and monitor. But it is also possible and even simpler to operate the system connected to the local network. In this case we can operate the system on an external computer or notebook using SSH with PUTTY or WinSCP and Xming to emulate monitor of Raspberry Pi. All these tools are freely available on the internet and we don't need extra keyboard, mouse and monitor.

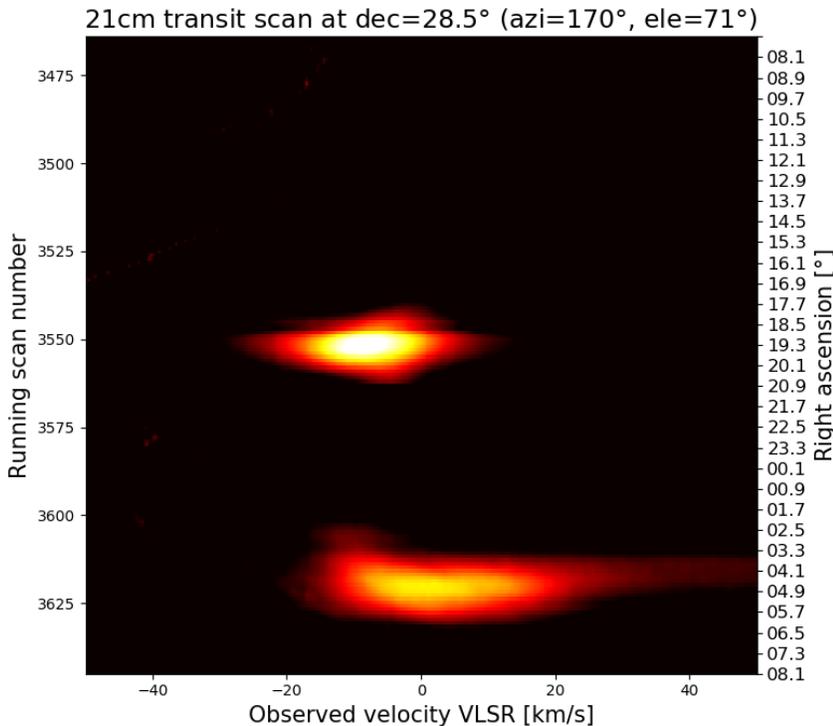


Fig. 6: Here we see a 24h observation at fixed telescope position. Left y-axis we see the running scan number, provided by the Raspberry software. Right y-axis the calculated right ascension where the dish was pointing to. and x-axis shows velocity with respect to local standard of rest (VLSR) in km per second. A clever background subtraction method gets rid of local interference and variation due to temperature changes. A Python script is available from the author to produce such a plot. The bright spot is close to Cygus A while the weaker but wider spot is near Taurus A.

If we repeat this scan as shown in figure 6 we can produce a velocity map along the galactic plane of our Milky Way. This kind of map demonstrates that the Kepler law doesn't work as expected which is an indication for

dark matter. Many nice plots of such velocity maps can be found on the internet, e.g. this one here:
https://www.astro.umd.edu/~richard/ASTRO421/MilkyWay_lec10.pdf

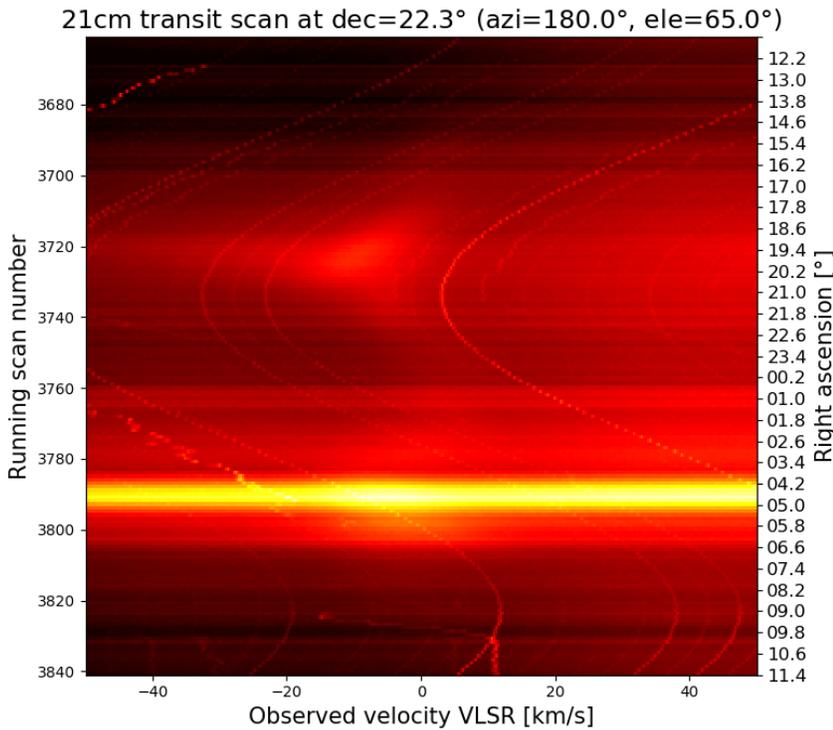


Fig. 7: Here we see a combination of neutral hydrogen (very weak), compared to a transit of the Sun. While the neutral hydrogen shows line profile in the order of +/- 50 km/se the Sun produces wide band spectrum with no spectral feature (bright yellow stripe). This stripe can be used to calibrate the hydrogen line intensity or brightness which can be expressed either in antenna temperature in Kelvin or in flux, expressed in Jansky of $W/m^2/Hz$. In addition it helps to check the telescope position because we know when we expect the Sun to transit through the antenna beam.

Nowadays all the components which are used to build up a radio telescope can be procured from different local shops or on eBay, Wish, AliExpress or any other supplier. I procured all components in Switzerland which are slight more expensive but get better support in case of problems.



Fig. 8: Typical software defined radio (SDR). There are many other, similar devices which allow to receiver frequencies up to 1420 MHz and to provide analog-digital converted data via USB-cable to a computer for further data analysis. I tested many other (cheaper) SDRs in form a a USB-stick. But data quality proved to be best with this SDRplay.

Important to note that you buy a Raspberry Pi with at least 4GB of memory, otherwise software will not work. Also important that the power adapter can supply sufficient current to feed not only Raspberry but also the SDRplay and optionally keyboard, mouse and monitor.



Fig. 9: Typical Raspberry Pi as backend for the radio telescope. In my case I use both ways to communicate with Raspberry.

- a) With keyboard, mouse and local monitor
- b) With my house internal network to remote access the system from my notebook.

Don't forget to order a SD-card with 32 GB memory.

Links to buy from AliExpress:

Components for a radio telescope to be ordered from AliExpress

Band pass filter BPF:

https://de.aliexpress.com/item/32432572469.html?spm=a2g0o.productlist.0.0.24302414avkCzP&algo_pvid=51fa96bc-30aa-4a01-a768-a1e4b9b0d8a1&algo_expid=51fa96bc-30aa-4a01-a768-a1e4b9b0d8a1-10&btsid=0ab6f8ad15902444001276823ee947&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_

Receiver RX:

https://de.aliexpress.com/item/4000317752046.html?spm=a2g0o.productlist.0.0.26467b260VcNUN&algo_pvid=def190cc-828d-4ba3-9fc7-760156fa608c&algo_expid=def190cc-828d-4ba3-9fc7-760156fa608c-26&btsid=0ab6f8ad15902444628051186ee947&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_

Computer:

https://de.aliexpress.com/item/4000054878108.html?spm=a2g0o.productlist.0.0.79b921fblwavNR&algo_pvid=86332f49-712d-4c96-8c82-0b391f725312&algo_expid=86332f49-712d-4c96-8c82-0b391f725312-9&btsid=0ab6f8ad15902445058733042ee947&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_

SD card:

https://de.aliexpress.com/item/32676225311.html?spm=a2g0o.productlist.0.0.6c783779bcK8G7&s=p&ad_pvid=20200523073623499231047226600004488049_2&algo_pvid=e53743b6-8716-4f08-b6dd-6cdfc752c027&algo_expid=e53743b6-8716-4f08-b6dd-6cdfc752c027-1&btsid=0ab6f8ad15902445831475595ee947&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_

Low noise amplifier LNA:

https://de.aliexpress.com/item/4000698118988.html?spm=a2g0o.productlist.0.0.11317e10rPzDUD&algo_pvid=30faa2fd-0fce-445d-b8fd-389b9105a2cb&algo_expid=30faa2fd-0fce-445d-b8fd-389b9105a2cb-

17&btsid=0ab6f8ad15902446492771109ee947&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_

Dish:

https://de.aliexpress.com/item/32810348685.html?spm=a2g0o.productlist.0.0.4960133c1zncz2&algo_pvid=6095c708-9682-4dbb-9d38-b59ec11fc049&algo_expid=6095c708-9682-4dbb-9d38-b59ec11fc049-28&btsid=0ab6f8ad15902447235916159ee947&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_

Links to buy from Digitec.ch:

Anzahl Artikel	Bestellnummer	Preis
1x Raspberry Pi 4 4G Starter Kit	11764848	109.00
2x Stück Samsung micro SDHC 32GByte	6304643 je 14.90	29.80
1x SDRplay Radio Spectrum Processor RSP1A	9937729	141.47
1x Adapter Micro HDMI HDMI	2481875	13.30 (optional)
1x Adapter Mico HDMI VGA	10282474	19.90 (optional)
1x USB-Kabel A-B 2m	219717	6.90
1x USB Maus	5829287	21.70
1x USB-Keyboard German	10149269	32.90

Links to access software and additional information from astropeiler.de:

Home page here: <https://astropeiler.de/>

'21cm mit einfachen Mitteln': <https://astropeiler.de/beobachtungen-der-21-cm-linie-mit-einfachen-mitteln>

'Ein transportables Radioteleskop für Schulprojekte':

https://astropeiler.de/sites/default/files/Astropeiler_1.2m.pdf

This document also contains more links to get the handbook for CLASS as well as links to download software running on Raspberry Pi. Or, you may get a copy from me.



Christian Monstein is a native of Switzerland and lives in Freienbach. He obtained Electronics Engineer, B.S. degree at Konstanz University, Germany. Christian is a SARA member and is licensed as amateur radio operator, HB9SCT. He has 21 years of experience designing test systems in the telecommunications industry and is proficient in several programming languages including C++, IDL and PYTHON. He has worked at ETH-Zürich on the design of a noise transmitter as payload on a drone and is responsible for the hardware and software associated with the e-CALLISTO Project. He also contributed to the HERSCHEL space telescope as well to the MUSE at the VLT in Chile. He plays also the role of a coordinator of SetiLeague in Switzerland and he is also representing Switzerland within CRAF. He is a member of the ISWI steering committee at UN office for outer space affairs in Vienna (UNOOSA) and has just been nominated as member of ITU. Email contact: [monstein\(at\)irsol.ch](mailto:monstein(at)irsol.ch)