

Low Cost Hydrogen Line Radio Telescope for £160 using the RTL SDR

David Morgan has written two excellent articles on Measurement and Analysis of the Hydrogen Line¹ and Experiments with a Software Defined Radio Telescope². This was the inspiration to have a go to see what could be achieved with minimum expenditure. Figure 1 shows the resulting schematic and Figure 2 the receiver implementation. Total cost apart from the laptop is about £180. The RF switch isn't really necessary and drops the total cost to £160.

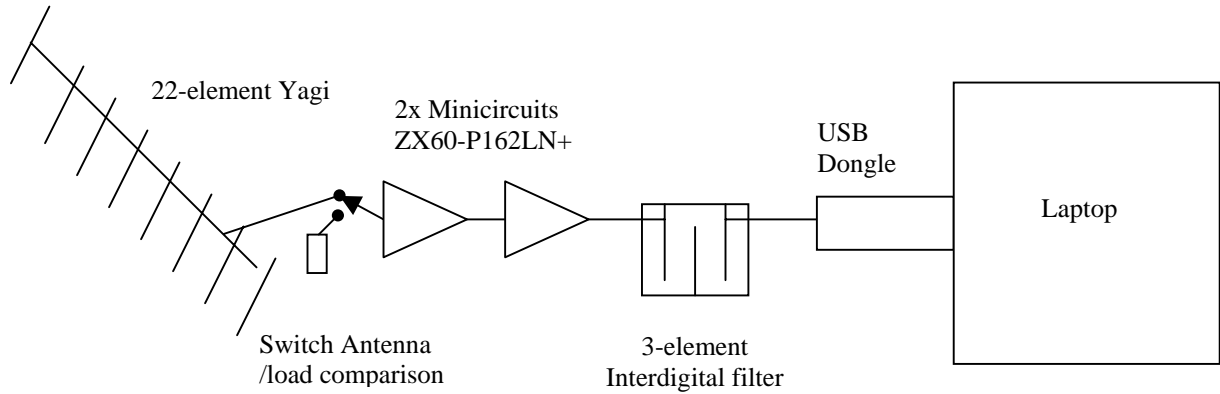


Figure 1. Simple Radio Telescope

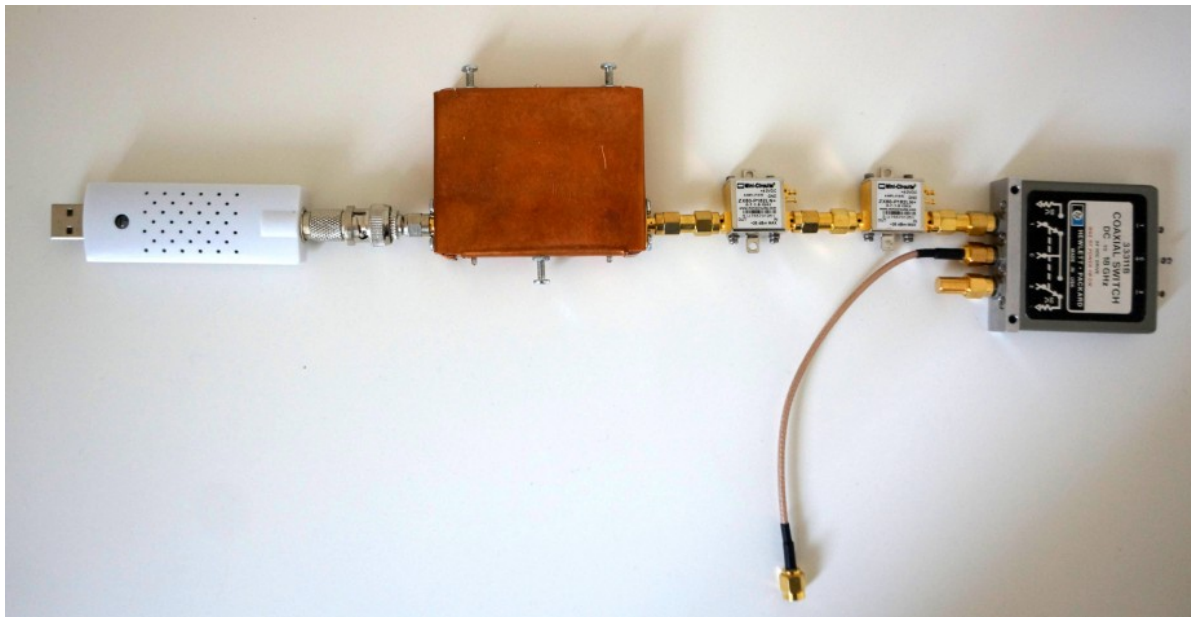


Figure 2. Basic Hydrogen line receiver

Antenna (£10)

The antenna constructed for ease of testing through a bedroom window comprised a 1.5m length of 2cm x 1cm hardwood with 1.6mm brazing rod elements screwed to the hardwood. It was designed using P. McMahon's YagiCAD³ and based on DL6WU20 file in the software 'Example Models' list. The CAD software allows the design to be re-tuned to 1420MHz – the impedance comes out close to 50ohms with a good front-to-back ratio. Beamwidth is 26deg and gain about 18dB. Figure 3 shows the antenna with an inset detail of the construction.

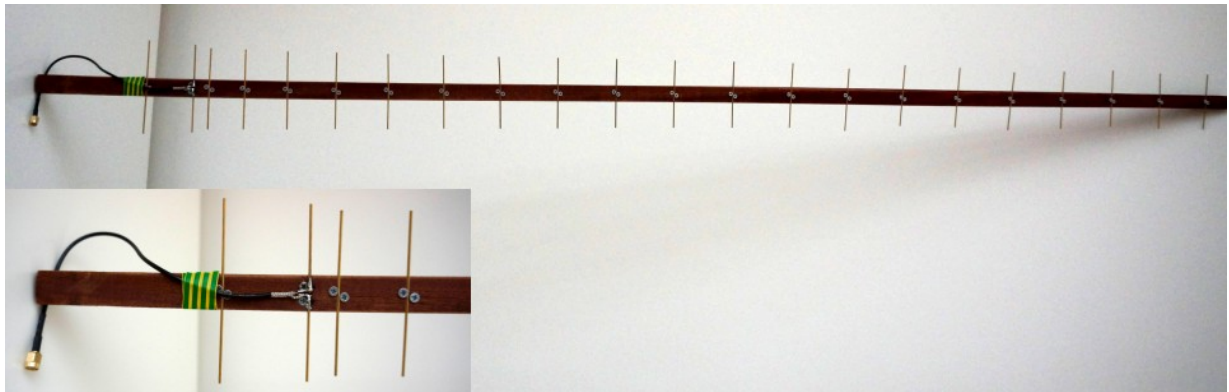


Figure 3. Simple 22-element Yagi

Switch (£20)

A single pole 2-way RF switch (Figure 2) provides a reference for comparing and calibrating the signal received from the antenna. In a Dicke switched receiver this is toggled at audio rates and integrated in an analogue manner. It is simpler in a digital system to average the received spectrum output first for the signal followed by the reference and carry out the comparison in subsequent file processing in Excel for example. In fact, the switch may not be necessary and the switch loss avoided if the user is prepared to disconnect the antenna and fit a matched load to the receiver input and integrate to obtain the reference measurement.

Amplifiers (£110)

These are Minicircuits ZX60-162LN, about 20dB gain and 0.6dB noise figure at 1.4GHz. They each require 4V at 50mA. A reasonably cheap power supply solution was a 20VA, 230V primary, 9V secondary transformer and a Voltage Regulator kit, AC in DC out based on the LM317, both procured via ebay. The Minicircuit's amplifiers cost about £46 each +vat and postage. Lower noise figure (0.25dB) amplifiers are apparently available from S Jewell G4DDK⁴ at around £50 for a kit.

Filter (£20), Cables and Connectors (£5)

The narrow-band filter was designed using an excellent internet calculator⁵ by D. Heatherington WA4DSY and following construction ideas from the Utah ATV Page⁶. I opted for a 5MHz 0.1dB bandwidth 3-element filter. A 0.9mm copper sheet was cut out and bent around sized wooden blocks for the box and lid. 14 gauge tinned copper wire cut for the interdigital elements and SMA connectors for input and output. The input and output connections to the elements needed care to solder as they were about 1mm from the element (box) end as is evident from Figure 4.

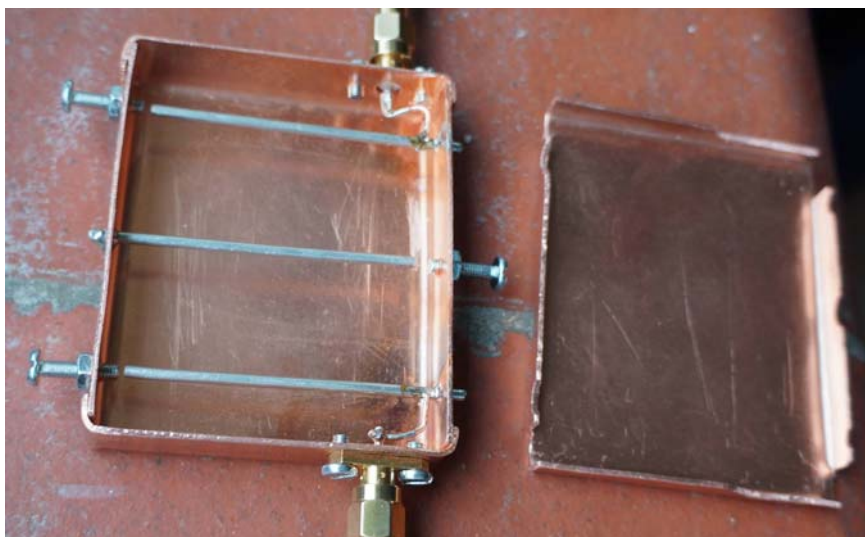


Figure 4. 3-element Narrow Band Interdigital Filter

Tuning is easy for a 3-element first you maximise the centre element then trim the outers using the dongle with SDR# software and monitoring the displayed receiver noise level. By tuning the dongle centre frequency in 1MHz increments either side of 1420MHz the receiver noise amplitude follows the filter characteristic. Performance achieved was 6MHz 0.1dB ripple bandwidth and 16MHz 20dB bandwidth. Initially, this filter tuned 10 MHz but by shortening the centre element (obvious as the tuning screw fell out) success was achieved. Minicircuits offer a filter 100MHz bandpass from 1350 to 1450MHz, but the filter roll-off is too slow to effectively reduce interference. The lid should be soldered or sensibly clamped to ensure stable performance.

Receiver

Option A (£157): The FunCube Dongle⁷ (FCD) using SpectraVue⁸ software.

SpectraVue has some useful options for collecting, outputting and processing radio astronomy data. The dongle has 96kHz bandwidth for 192kHz I+Q sampling rate but with the software minimum Fast Fourier Transform (FFT) size of 2048, requires a long observation time with a lot of averaging to achieve an acceptable sensitivity.

SpectraVue provides a useful spectrum display with facilities for FFT averaging.

In the radiometer equation, the temperature sensitivity, $dT/T = 1/\sqrt{(nbt)}$, where the FFT bin bandwidth, $b = 96\text{kHz}/2048 \sim 47\text{Hz}$, and the FFT data collection period, $t = 2048/96\text{kHz}$. Averaging 'n' FFT bins for 100sec, then, $\sqrt{(nbt)} = 68.5$

(Note: $bt = 1$ for any single FFT bin for any number of FFT points and clock rate - all the sensitivity benefit comes with the averaging!). In practice, with reasonable observation times, useful, but noisy hydrogen line spectra can be obtained (Figure 5) – the figure shows four overlapping FFT 96kHz spectra covering the frequency range 1419.95 GHz to 1420.2GHz, each covering 96kHz.

This dongle wasn't frequency calibrated and there was known interference from PC's close by. Improved performance was noted when interfering sources were located, screened or switched off.

Data shown is the ratio of the signal from the antenna to the signal (noise) measured when the input is switched to a reference load. Ideally, this removes the receiver gain response and allows temperature calibration – this is demonstrated in the paragraph 'Temperature Calibration' below.

SpectraVue has the capability of outputting files of averaged FFT data and also, raw IQ data in .wav formatted files.

The dongle narrow bandwidth and the software minimum FFT size, makes this a poor receiver choice for hydrogen line work. If the software FFT size were reduced to 32 points (~3kHz bins) this would give an 8-fold reduction in noise, much improving the data quality and receiver sensitivity. To get an equivalent improvement by alternatively extending the observation time, means an increased dwell time from 100sec to more than 1.75hrs.

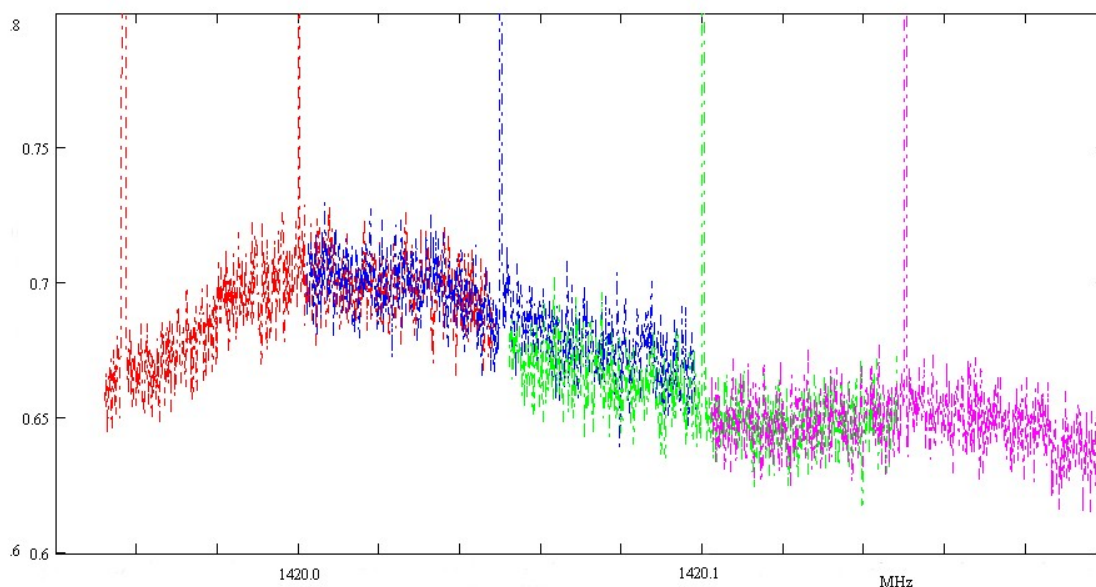


Figure 5 FunCube dongle receiver spectra

Option B (£15): The Realtek RTL2832U DVB-TV dongle (RTL) is compatible with SDR# software⁹ and needs the Zadig¹⁰ driver for WINDOWS. For Hydrogen line astronomy, the SDR# spectrum displays are not very useful containing only time-constant variable attack and decay on FFT bins. There is, however the facility to record .wav formatted files of I/Q samples at clock rates typically 2.048MHz offering a 2MHz analysis bandwidth suitable for processing off-line.

OsmoCom¹¹ have produced an 'rtlsdr' library & capture tool. The capture tool produces files (.bin) containing raw IQ data for later analysis and can be viewed using programs such as 'hexdump.exe'. A good description of the rtlsdr tools and data analysis procedure is given in reference (12).

As an alternative, a Java applet¹³ and .exe¹⁴ programs have been written to accept OsmoCom captured data to average FFT spectrum results and output text files that can be further processed and viewed in Excel or MathCad.

The Java applet is useful for quick assessment of shortened records, but using browser applet viewers can be very slow to analyse large data blocks. The alternative RAFFT.exe FFT averager program is written in 'C' and is about 30 times faster, averaging data in about the same time as for the data acquisition.

Since both 'signal' and system noise are both zero-mean random noise there is little benefit gained from input data windowing, such as 'Hanning' etc: before computing the FFT spectrum.

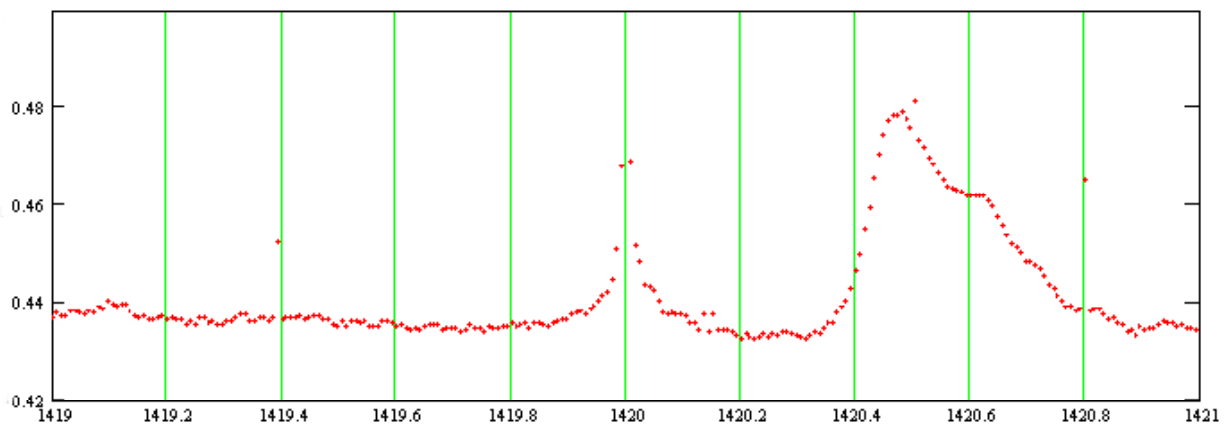


Figure 6 RTL2832U dongle receiver 256-point spectra for Galactic Longitude 145°

Figure 6 shows the Figure 1 receiver response when directed at Galactic Longitude 145° for two 97sec periods. The first period collected data using OsmoCom software rtl_sdr.exe to output a .bin file with alternate I and Q amplitude data via the antenna. The resulting file was then processed by C-programmed software RAFFT.exe – this inputs the .bin file and carries out almost 400,000 256-point FFTs, and averages these to improve the temperature sensitivity over 600 times.

The second period collects similar data when the receiver input is terminated by a reference load. Figure 6 plots the ratio of the two resulting averaged FFTs processed by the RAFFT.exe program.

The central spike is a dc offset feature and the central broadening is due to dongle VCO noise and it is also noted a few spurious points occur. Again, the receiver has not been frequency calibrated but the hydrogen line components are obvious and compare favourably to that collected by more complex systems¹⁵. The ordinate is the measured result of taking the ratio of signal record to matched load input record.

The VCO feature can be removed by more receiver gain to better match the input noise signal to the dongle ADC dynamic range. Figure 7 shows improved performance by using a third 20dB gain RF amplifier, increasing the front-end gain to 60dB leaving the dongle gain max at 42dB so that the overall gain exceeds 100dB. Unfortunately pushing the budget up by another £55!

In Figure 7, using two 97sec rtlsdr .bin files of antenna and load inputs and RAFFT.exe averaging program, and finally, dividing the resulting text data, the plots show,

red plot: Galactic longitude 155°, 0° latitude. - typical hydrogen line plot.

black plot: Galactic longitude 145°, +25° latitude, - cold region, but slight bump at 1420.4MHz, zero relative velocity, is easily visible, so checking the RTL dongle frequency calibration.

blue plot: Galactic longitude 195°, +10° latitude but directed at the sun, baseline shift shows sun temperature and also hydrogen line (the antenna beamwidth is 26° so encompasses hydrogen line

response at 0°deg galactic latitude). A rough temperature calibration is marked, with the conclusion that there is probably quite a lot of antenna sidelobe thermal noise intercepted.

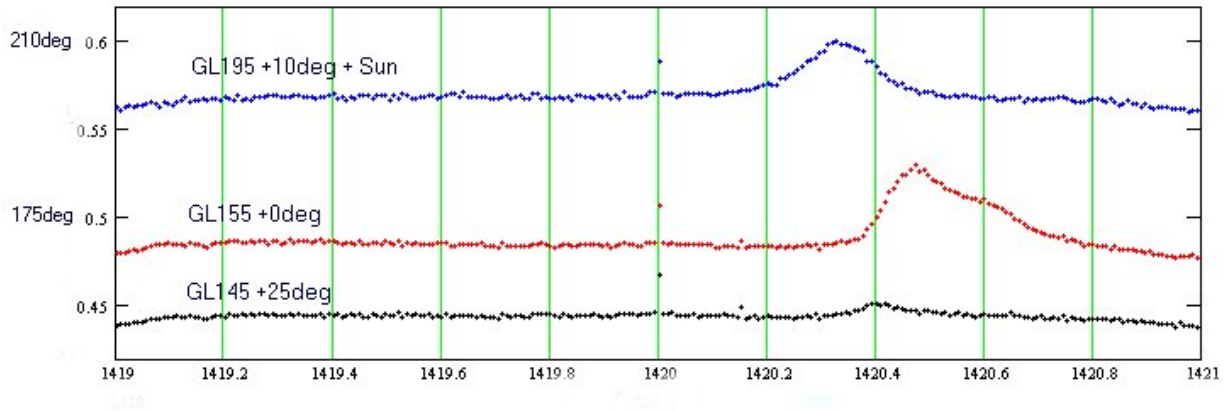


Figure 7 Improved performance with extra RF Gain

Temperature Calibration

If $G(f)$ is the power gain of the receiver as a function of frequency,
 b is the receiver analysis bandwidth
 T_a the wanted signal equivalent temperature
 T_{rx} the receiver noise temperature
 T_{ref} the reference load temperature
 T_u the unwanted noise components (background, sky, sun and ground temperature entering the antenna sidelobes).
 T_c the noise generated in the antenna connecting cable.
 k is Boltzmann's constant

When switched to the reference input load, the receiver output noise power is

$$P_{ref} = k(T_{ref} + T_{rx})bG(f)$$

When switched to the antenna, the receiver output noise power is

$$P_{sig} = k(T_a + T_u + T_c + T_{rx})bG(f)$$

The ratio R is simply,

$$R = (T_a + T_u + T_c + T_{rx}) / (T_{ref} + T_{rx})$$

For example, for the RTL dongle, $T_{ref} = 290^\circ$, $T_{rx} = 75^\circ$ (0.65dB amplifier noise figure, 0.2dB switch loss and 0.2dB connectors).

$T_c = 14^\circ$ for 0.2dB antenna connector and cable loss.

Minimum and maximum ratios R in Figure 6 are 0.43 and 0.48.

Therefore assuming the ratio 0.43 corresponds to no signal (equivalent ground/cold sky ratio = 3.7dB), but unwanted noise. We can calculate T_u and T_a as,

$$T_u = 71^\circ \text{ and } T_a = 18^\circ$$

Atmospheric emission and background noise at this frequency are about 3° each. The efficiency of a Yagi antenna should be better than 90%, so unwanted ground noise should be less than 29° ! Let's say it is only 80% efficient, then unwanted ground noise rises to 58° seems to fit the figures

A rough calculation of the signal noise (T_a) follows. The antenna beamwidth is 26° so the expected measured signal temperature of a 100° Kelvin hydrogen cloud angular extent $5^\circ \times 30^\circ$ is 17° , which appears about right.

Similarly for the sun, assuming the subtended angle is 0.5° and equivalent surface temperature 70000°K ¹⁶, the expected equivalent temperature with the antenna pointed at the sun is, $70000 \times 0.25/26/26 = +26^\circ$.

Since the value for T_a is reasonable but T_u is not, there is also the possibility that the antenna copper losses may contribute – 0.5dB loss would account for 35° . There is also possibly some man-made noise being intercepted still.

Signal Integration/Temperature Sensitivity: The system temperature T_{sys} from the previous section is $T_{\text{sys}} = T_a + T_u + T_c + T_r$ and with integration, the temperature resolution is $T_{\text{sys}}/\sqrt{(nbt)} = 175/68.5 (= 2.5^\circ)$ for the FunCube dongle and $175/600 (= 0.3^\circ)$ for the RTL dongle.

Considerations, Limitations and Improvements

Interference: Beware of local interference in the range of the antenna. Personal Computer clock systems radiate significantly in band, local wifi, smartphones, smart tv and ipads etc: should be treated with suspicion. Wrap the dongle in aluminium foil and build a foil-covered box to house the laptop.

Antenna: Beamwidth is approximately $60/d$ degrees, where 'd' is the aperture in wavelengths. Hydrogen clouds in galactic arms lie within about 5° latitude; antennas with this beamwidth can be expected to have good temperature detection and moderate angular resolution. Beamwidths greater than this lose out on resolution but more importantly, on detection and temperature measurement loss equivalent to the proportion of beam not illuminated in latitude. Wide beamwidth antennas also tend to allow greater unwanted ground noise into the system through sidelobes. Narrower beamwidths have full temperature sensing ability, can control spillover loss and are also able to resolve temperature variations in latitude and longitude.

RF Amplifier Noise Figure: Generally, the lower the better; below 1dB noise figure, however, the benefit of further reducing noise figure may not be very evident for broad-beamwidth antennas whose back and sidelobes illuminate the ground and local warm features, so raising the system temperature. For example, to obtain the same temperature uncertainty, the integration time for the system described with 0.65dB noise figure might only have to be double that required when the pre-amplifier is replaced with a 0.25dB noise figure device.

Total Receiver Gain: Gain should be sufficient to ensure that the dongle ADC range is fully utilized. This can be checked on screen using a relevant SDR software package such as SDR#.

Temperature affects amplifier gain and because of the high effective system sensitivity, there may be drift between successive measurements, which can affect temperature calibration accuracy. An optimum solution is for receiver baseplate temperature control. The alternative is to wait for devices to warm up and shield the receiver from the sun and draughts.

FFT points and clock rate: The data clock rate defines the dongle operating bandwidth (equal to the clock rate – RTL, and equal to half the clock rate – FCD). The rule is that the more samples processed, the better the frequency resolution. The trade off is time. The product of the bin width (resolution) and the data sample period is 1. The number of sample periods averaged is the integration time required to get a reasonable signal-to-noise ratio. So the better the resolution required the longer the time is needed for the antenna to dwell on a chosen direction. Since the line width of hydrogen is significant, due to velocity variations of gas in the observed cloud there is a sensible limit to the resolution required to infer cloud velocity components.

Conclusions

It appears that this basic technique using a simple antenna can provide a useful platform for detecting and studying the hydrogen line. It is evident that smaller beamwidth, more efficient antennas would considerably improve the data quality.

Comparing dongles, the broader bandwidth of the Realtek RTL device makes this a better choice.

Comparing SDR software, both FCD and RTL dongles can be used with SDR#, but the software is not well-matched for hydrogen line radio astronomy. FFT averaging of hundreds of thousands of samples is required to achieve the required sensitivity but the SDR# software has only a limited averaging form.

SpectraVue does not support the RTL dongle but has a good averaging function although FFT size is too

large and very long observation times probably requiring tracking may be necessary unless of course you are blessed with a multi-metre dish.

Both software packages do provide a raw data file output in .wav format that can be processed off-line.

RAFFT.exe provides this function but in its basic form, reverses the spectrum and may slightly corrupt the data by processing the header. The plan is to update RAFFT.exe to operate correctly on .wav files.

More information available at <http://www.y1pwe.co.uk/RAProgs/index.html>

Final Observation

From an amateurs' point of view, there appears to be an optimum solution for detection and analysis of hydrogen in the arms of our galaxy. The RTL receiver and processing as described, but using an antenna with around 2m aperture (beamwidth of the order of 6deg). This is sufficient for full SNR detection and temperature measurement of galactic hydrogen with moderate angular resolution in both latitude and longitude. The FFT frequency resolution as described does not require antenna tracking and is sufficient to indicate and separate the galactic arms.

Increased demand for better angular resolution requires larger dish apertures. Better frequency resolution requires longer dwell times and therefore accurate tracking of the antenna pointing direction.

References

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13. <http://www.y1pwe.co.uk/RAProgs/RadAst.htm>
14. <http://www.y1pwe.co.uk/RAProgs/RAFFT.exe>
15. <http://astro.u-strasbg.fr/~koppen/ISGH5/index.html>
16. Burke BF. Graham-Smith F. "An Introduction to Radio Astronomy (Second Edition)", 2002.

Appendix - Post Processing

Both OsmoCom rtl tools and the FFT averager are run in the command line. The procedure for this is described below.

1. Copy 'Command.com' from C:\WINDOWS\system32\ to your working folder/directory, placed on the Desktop
2. Open 'Command.com' check that it is initialised in your working directory.
3. Type, **doskey** and press the keyboard Return key. This allows the up/down keys to be used to remember earlier commands for ease of editing and repeating..
4. To record data to .bin files, type on the command line... **rtl_sdr.exe ./capture1.bin -f 1420e6 -s 2048e3 -g 42 -n 200e6**
-tunes to 1420MHz, samples both I and Q ADC's at 2.048MHz, sets dongle gain at 42dB and records 200million I and 200million Q samples interlaced in the output file. The output file capture1.bin is stored in the current folder
5. To perform and average 256-point FFT spectra.... **RAFFT.exe capture1.bin capture1.txt 256**
- the output capture1.txt file stored in the current directory can be input to Excel or any math cad program to compare pairs of load and antenna files to view hydrogen line spectrum.