Low Cost Hydrogen Line Radio Telescope using the RTL SDR - Phase 2

Abstract

Detecting the hydrogen line in the arms of our galaxy using modern technology is now easy. Key available components are low-noise RF amplifiers and software-defined radio (SDR). With a home-made Yagi, a couple of amplifiers, a cheap RTL2832U TV dongle, a bit of effort and some free software, for well less than £200 you can be up and running measuring the velocity and positions of the spiral arms, some tens of thousands of light years away. This paper describes the phase 2 upgrade, improving both the receiver and the antenna, now mountable on a tracking telescope mount, able to position the antenna for serious galactic equator measurement. Early results show good repeatable performance and with a bit of mathematics plots some arms of our galaxy.

Introduction

In the basic receiver paper[1], it was recognised that improved antenna directivity was worth striving for. In addition in the upgrade, more RF gain was added to better utilise the SDR ADC range and extra RF filtering added to minimise interference. The new antenna construction design was aimed to make it compatible with a driven equatorial telescope mount (Celestron CG-5 Advanced GOTO Computerized Mount ~£500). A home made Alt/Az timber structure was considered, but the lure of GOTO to automatically direct the antenna accurately and painlessly was deemed worth the cost.
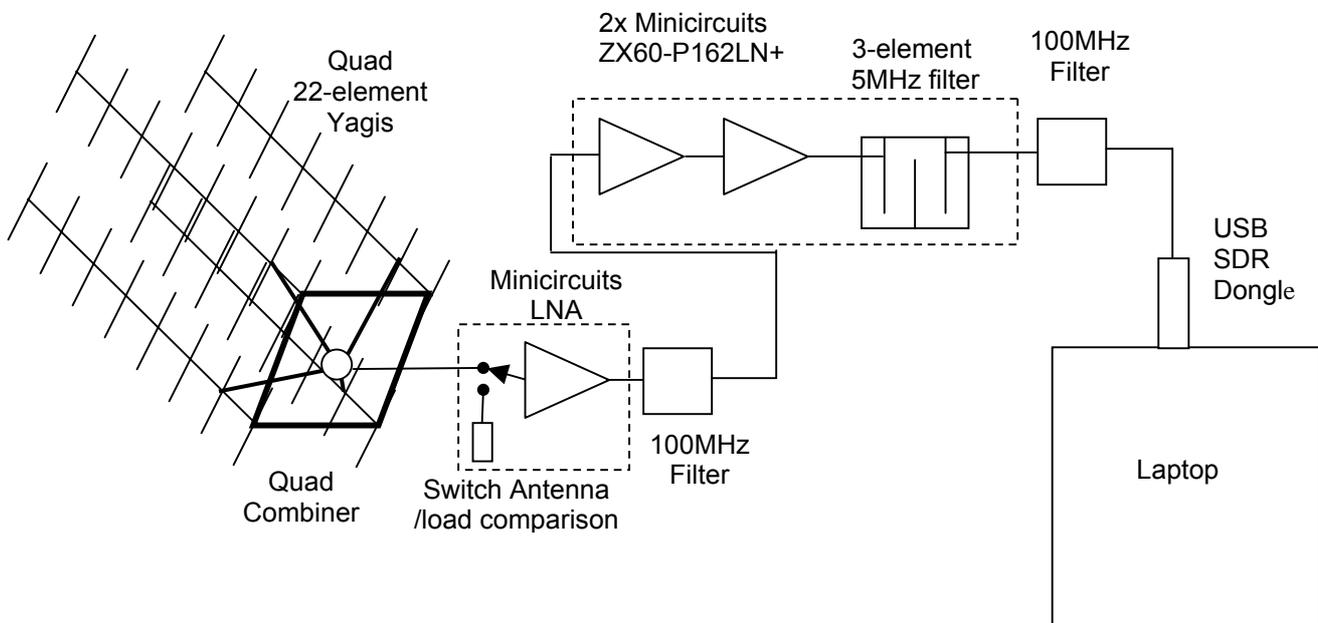
Figure 1. Simple Radio Telescope Upgrade

Figure 1 shows the upgrade schematic. The receiver is now boxed in two units, one closely attached to the antenna and the second, remotely near the SDR/Laptop processor.
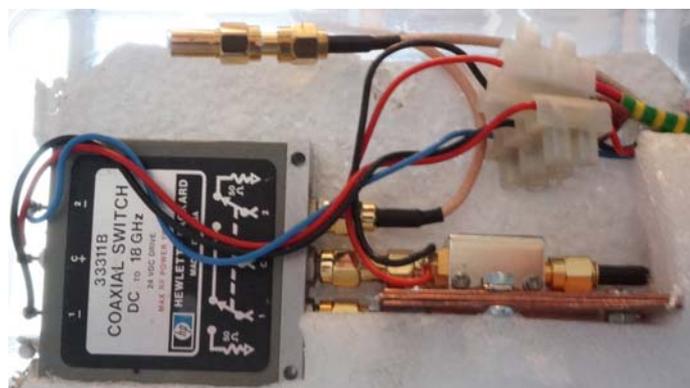
Figure 2 Switch/Preamplifier Unit
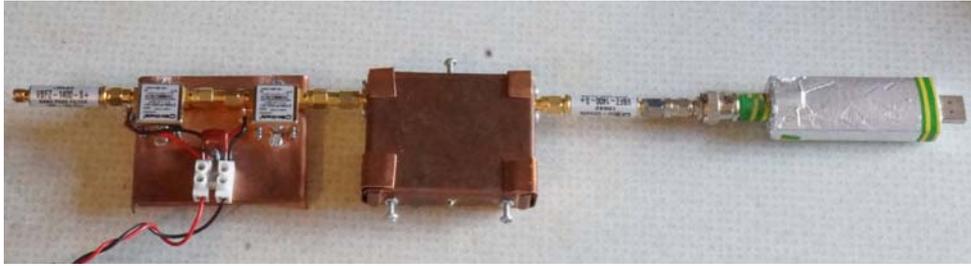
Figure 3 RF Filter/Amplifier/SDR Unit

The RF units shown in Figures 2 and 3 are normally boxed and shielded.
Most of the components such as the switch, load and the 5MHz narrow-band filter are as used in the previous article[1]. Figure 3 also shows the 100Mhz filters supplied by Miniciruits (£30 each), which were shown to be necessary to cope with neighbouring high power PC's. These could also have been produced using the 5MHz filter design package[2].

Antenna (£50)
The antenna upgrade (Figure 2) involved a redesigned Yagi in a quad array, but still based on the original design. Again it was designed using P. McMahon's YagiCAD[3] starting with the DL6WU20 file in the software 'Example Models' list. For this design, the software was used to optimise the design at 1420MHz by tuning the centre frequency lower to 1390MHz and using the wide band optimiser and displays to improve the gain, match and back-lobes at 1420MHz. Beamwidth now is around 13deg and gain about 24dB. Figure 2 shows the antenna with an inset detail of the construction.
The booms comprise bolted back-to-back 9.5mm aluminium U-channel 1.5m sections. Bronze welding rod 1.6mm diameter elements are clamped between the U-sections, predrilled and insulated with heat-shrink sleeving. The driven dipoles are similarly clamped but mounted in drilled perspex rod.
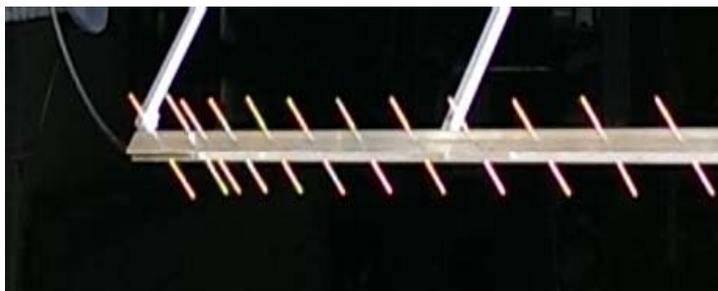
Figure 4. Quad Yagi Array on C-5 Mount

The array is balanced and supported by 1" square tube which slots over a 3/4" bar and plate mounting structure.

Antenna Combiner - 3 versions
1. Coaxial line 1/4 wave transformers - home-cut coax lines
In Figure 5a, paralleling the upper two antennas drops the impedance to 25Ω, the 50Ω quarter-wave transformer converts this to 100Ω. Similarly for the lower pair of antennas.
Combining the two quarterwave lines halves their 100Ω output impedances to 50Ω, matching the output 50Ω transmission line.
Keeping the feed lines of equal lengths and multiples of 1/2 wavelength helps to accommodate small variations in the four Yagi input impedances which ideally are resistive 50Ω.
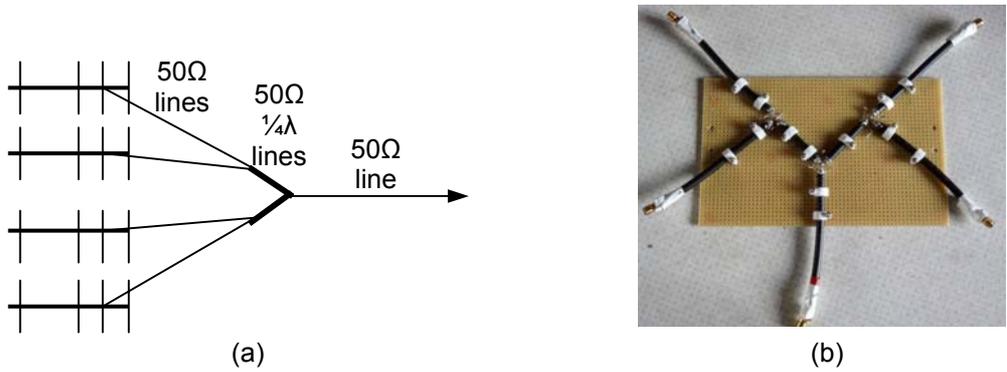
Figure 5. Combining Four 50Ω antennas.

2. Coaxial line 1/4 wave transformers - connector assembly

An alternative to cutting and soldering lengths of coax, is to assemble SMA connectors and adapters to good approximation as shown in Figure 6. Various adapters are used to adjust the arm lengths to 1/4 wavelength.

Figure 6. Connector combiner

3. Power Divider/Combiners

Matched combining using commercial power combiners, is best tolerant of Yagi source mismatches as shown in Figure 7.

Figure 7. Power Divider/Combiner

Minicircuits sell a combiner for this band (~£50) but some are available from China on ebay for £15. Comparing these three options in place, (3) gave the most consistent results but insertion loss and system temperature was highest. (2) gave the least loss but in both (1) and (2) mismatch differences between the Yagis was evident but some tuning of a Yagi driver element length improved the situation. It is concluded that with the right test equipment, both (1) and (2) 1/4-wave transformers could be optimised to cope with antenna manufacturing and design differences and give the lowest system temperature.

SDR Receiver (£10)
The Realtek RTL2832U DVB-TV dongle (RTL) is compatible with SDR# software[4] and needs the Zadig[5] 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. However it is very useful for locating interfering sources and checking efficient and proper operation of the receiver/RTL SDR.
Once the system has been checked, data is collected using the OsmoCom 'rtlsdr' library & capture tools[6]; the data files contain raw IQ data for later analysis. Versions are available for both Windows and Linux.
Data analysis uses the *RAFFT.exe*[7] FFT averager program for Windows or *rafft*[8] for Linux.
Two versions of the RTL2832U dongles have been compared. One using the E4000 tuner and the other, more commonly available now at very low cost, using the Rafael 820T tuner.

SDR Operation
Radio astronomy applications for SDR's require operation in a different regime to normal broadcast radio. For example, in conventional receivers, AGC is a common method to ensure that demodulation occurs in the optimum signal range and copes with variations of reception conditions and siting relative to transmitters. Radio telescopes on the other hand require constant gain, adjusted to an optimum for the target of interest, although there are cases where AGC is applied to the reference channel for Dicke switch reception.
With digital SDR's and conventional use, it is normally sufficient for RF/IF gain to be set so that system noise levels just exceed the minimum ADC threshold so that for most signals, the majority of the ADC amplitude range is available for the wanted signal. In radio astronomy, to minimise the effects of quantisation noise, the whole ADC dynamic range should encompass the noise-like target/reference amplitude response range.
This means that the RF amplifier chain and SDR IF gains need to be adjusted to ensure this applies. For H-line measurements this overall gain is typically around 90 to 100dB.
The software program *ASTATS.EXE*[9] for Windows (*astats*[10] for Linux) gives a graphical view of the ADC operating amplitude distribution.
The instructions in DOS / Linux terminals are of the form:
Windows: ASTATS.EXE <infile.bin> <outfile.txt>
Linux: ./astats <infile.bin> <outfile.txt>
The output text file showing the ADC amplitude distribution can then be displayed in Excel type spreadsheets or MathCad packages. The x-axis represents the ADC byte value and the y-axis the normalised byte value count.
Figure 8 shows some typical reference load *.bin* records.
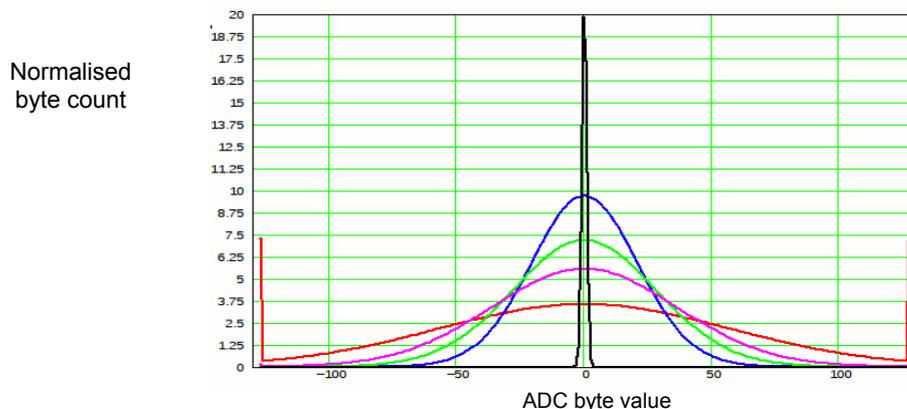
Figure 8 Some typical ADC amplitude distributions

Examples, blue and green in Figure 8 are acceptable; magenta and red show evidence of limiting at the ADC positive and negative extremes, possibly producing spikes in the resulting FFT. Insufficient RF gain is indicated by narrower spikes (black) around value zero point.

Measurements

Measurements summarised in Figures 9 and 10 were made at 0° Galactic latitude and at 10° longitude intervals over the visible galactic plane from 80° to 180°.
Right Ascension and Declination values for directing the equatorial mount to chosen Galactic Latitude and Longitudes were obtained from an online Universal Coordinates Converter[11].
Each data set comprised 200×10^6 samples taken over about 100 seconds. Data sets (see Appendix) were split into 256 sample blocks, the signal spectrum extracted using 'rafft' program and all FFT block sets averaged. Similarly for reference load measurements.
Output longitude spectra were then divided by the average of seven 100sec reference load spectra so providing the ratiometric[1,12] hydrogen line ratio responses shown in the figures.
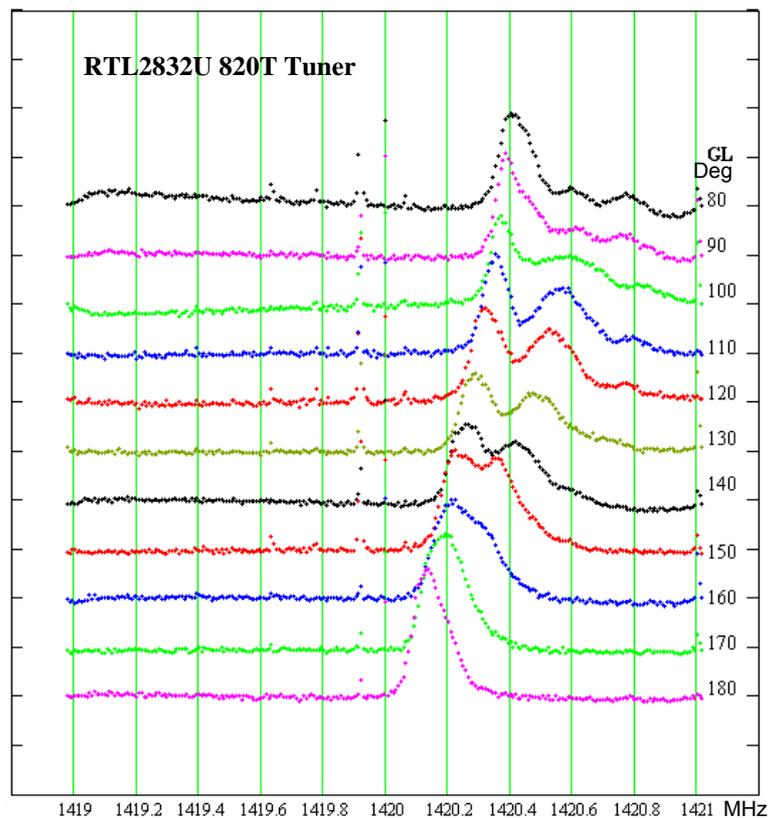
Figure 9. Spectral Display Measurements Galactic Latitude 0°, Galactic Longitude as marked

These raw results are as recorded; the frequency migration of the largest peaks (local arm) with angle is real and due the Earth/Sun platform vector velocity of the Local Standard of Rest (VLSR).
Correction velocities vary with the RA and Dec, and also with time. So each data set needs specific corrections, available from online calculators; Reference (13) was used for this project.
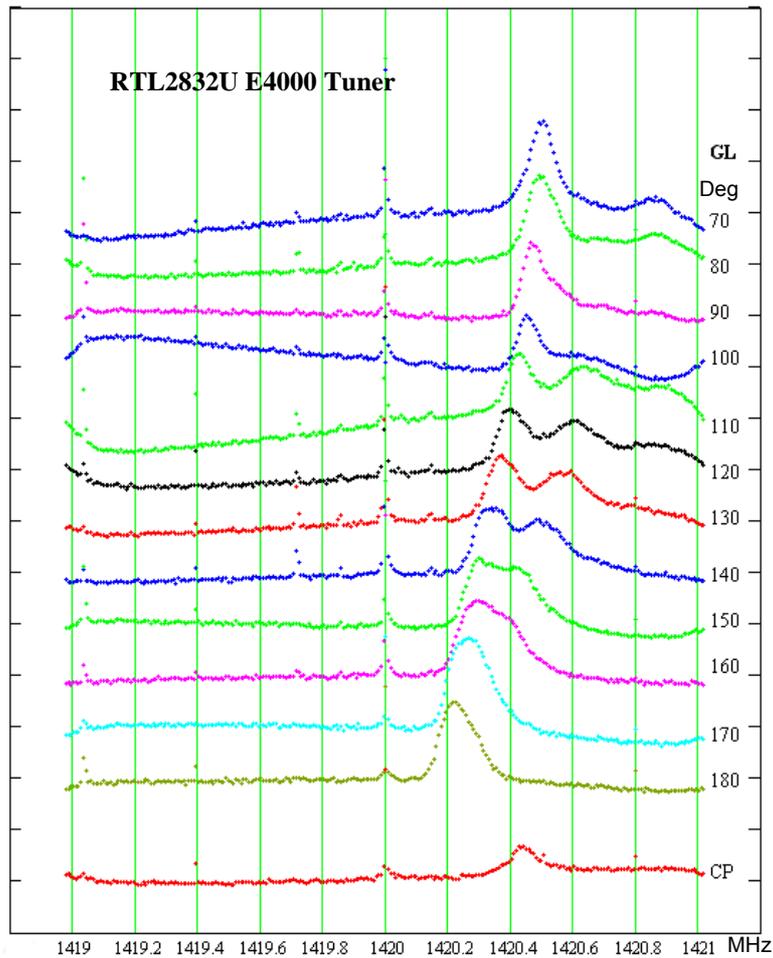
Figure 10. Spectral Display Measurements Galactic Latitude 0°, Galactic Longitude as marked

Included at the bottom of Figure 10 is a plot with the antenna pointed to the Celestial Pole where it might be expected that Hydrogen line Doppler shift may be low and therefore provide a reference calibration. Comparing Figures 9 and 10, it is clear that galactic longitude spectral measurements correlate well although there is obviously an SDR associated frequency offset. Both SDR's needed calibration correction, E4000 of 25kHz and the 820T of 100kHz.
Some external interference is evident affecting baselines of Figure 10 at GL < 130°

Plotting Galaxy Arms
Assuming the spectral peaks represent the centres of hydrogen clouds in the galaxy spiral arms, their positions can be calculated from the geometry of Figure 11. Given knowledge of the galaxy rotation rate (assumed constant with radius) and spectrum peak frequency/doppler velocities versus longitude; this is sufficient information to solve the triangles in Figure 11 to estimate the ranges to the corresponding spiral arm's hydrogen clouds.
A calculation example for GL = 120° is given to illustrate the method.
Firstly the spectral peak frequencies need to be converted into Doppler velocities, ie,

$$v_{doppler} = c.f_{doppler}/f_s = c.(1420.406 - f_{peak})/1420.406 \sim 211km/s/MHz$$

(c is velocity of electromagnetic waves = 3.10^8km/s)

At Galactic Longitude 120°, the three frequency-corrected velocities at the three spectrum peaks of Figure 9 are -96.8km/s, -44.5km/s, and 0km/s.
If V_{rot} is the mean rotation rate of the galaxy over the region containing the sun and galaxy arms of interest. $V_{rot} \sim 220$km/s, we can calculate the sun velocity in the direction of the hydrogen clouds from,

$$V_s = V_{rot}cos(120-90) = 190.5km/s.$$

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The three cloud velocities are then,
$V_0 - V_s$ = -0km/s, therefore, V_0 = 190.5km/s

Local arm: $V_0 - V_s$ = -0km/s, therefore, V_0 = 190.5km/s
Perseus arm: $V_1 - V_s$ = -44.5km/s, therefore, V_1 = 146km/s
Outer arm: $V_2 - V_s$ = -96.8km/s, therefore, V_2 = 93.7km/s

For Perseus arm, using, $R_1/\sin(120) = R_s/(V_1/V_{rot})$, then, R_1/R_s = 1.507
(this equation substitutes the relation, V_1/V_{rot} = cos b_1; where b_1 is the angle between the vectors V_{rot} and V_1 in Figure 11)
For Outer arm, using, $R_2/\sin(120) = R_s/(V_2/V_{rot})$, then, R_2/R_s = 2.348
The position of the clouds lie on the coordinates $R_1\cos[b_1 - (120-90)]$, $R_1\sin[b_1 - (120-90)]$ by substituting the sun-galactic centre ~ 30kly) range; similarly for the local and outer arms.
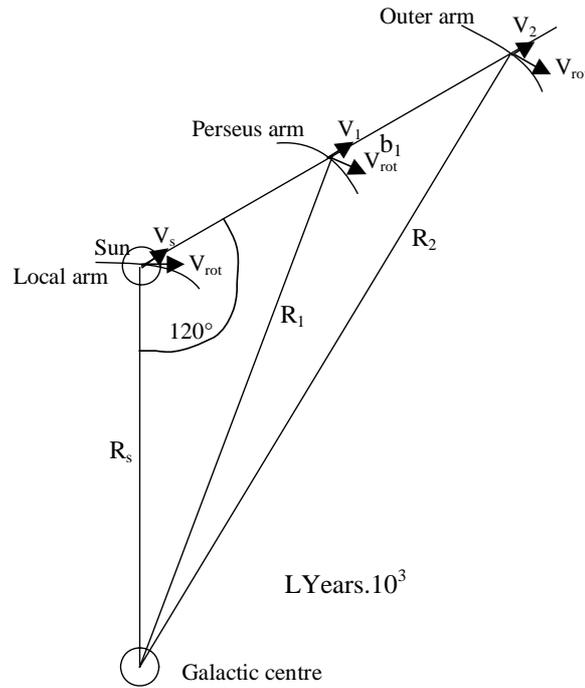
Figure 11. Plotting Galaxy Arms - example longitude 120°

Figures 12 and 13 summarise galaxy arm plots using data from Figures 9 and 10, after frequency calibration and corrected for the Earth's relative velocity in space using an online calculator[12] to derive the velocity of the Local Standard of Rest (VLSR).
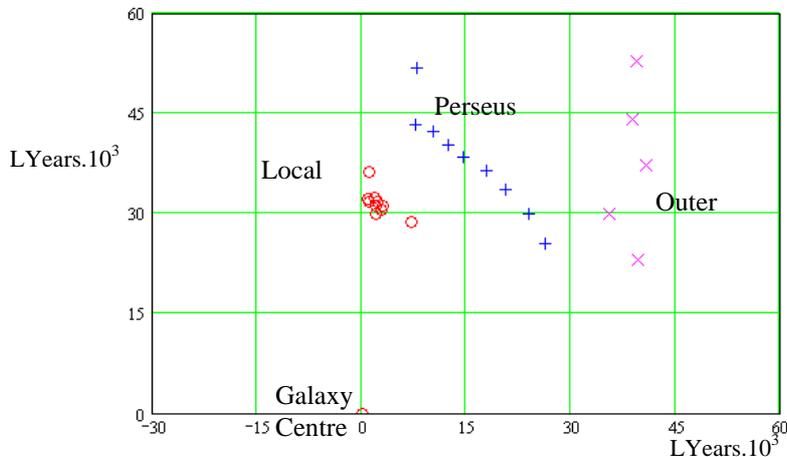
Figure 12. Galaxy arms plot using the SDR 820T tuner

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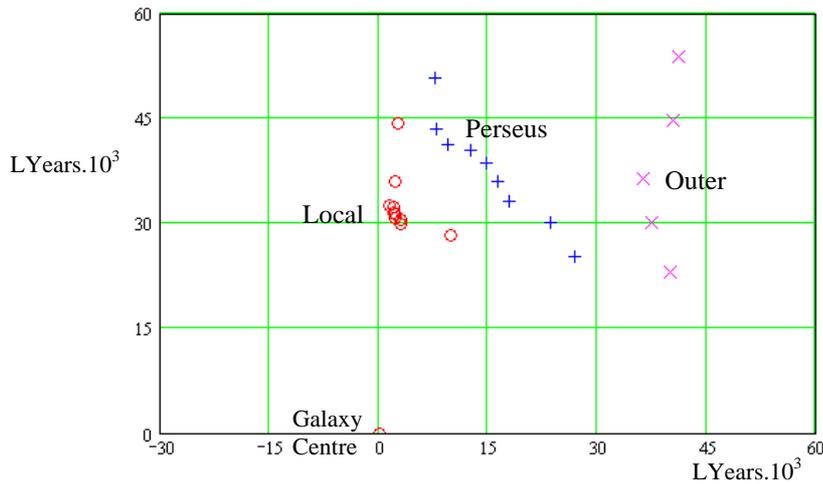
Figure 13. Galaxy arms plot using the SDR E4000 tuner

Figures 12 and 13 offer views of the presence of the spiral arms of our galaxy over a 90° galactic longitude sector based on manual identification of spectrum peaks in the analysed data presented in Figures 9 and 10. Although crude, trends are illustrated, although the calculations suffer from various inaccuracies. These include, noise in the spectra amplitudes affecting peaks, the broad spectral lines due to dispersion in the clouds and the wide longitude smoothing from the relatively broad antenna beamwidth. In addition, the geometrical calculations around 180° are not so tolerant of data and rotation rate errors.

Conclusions

It is interesting that with such a basic receiver and small antenna that it is possible to observe hydrogen clouds in our galaxy arms some 45000 light years away. A comparison of these charts with professional versions shows that they are crudely comparable.

The main difficulty in achieving these results is coping with local interference. Without the added 100MHz filters, at times the receiver was swamped and no hydrogen data was visible. In getting these results, it was apparent that receiver gain drift affected the baseline level. Drift was evident between successive measurements, so some form of temperature control or receiver architecture changes would be necessary to achieve more stable results. The SDR# software[4] was useful in locating local interference. More information available at http://www.y1pwe.co.uk/RAProgs/index.html

References

1. http://www.britastro.org/radio/projects/Low_Cost_H_Line_Telescope.pdf
2. http://www.wa4dsy.net/cgi-bin/idbpf
3. http://www.yagicad.com/YagiCAD/YagiCAD.htm
4. http://www.sdrsharp.com/index.php/downloads
5. http://zadig.akeo.ie/
6. http://sdr.osmocom.org/trac/wiki/rtl-sdr#
7. http://www.y1pwe.co.uk/RAProgs/RAFFT.exe
8. http://www.y1pwe.co.uk/RAProgs/rafft
9. http://www.y1pwe.co.uk/RAProgs/ASTATS.EXE
10. http://www.y1pwe.co.uk/RAProgs/astats
11. http://hea.iki.rssi.ru/AZT22/ENG/cgi-bin/c_prec4.htm
12. http://www.y1pwe.co.uk/RAProgs/Ratiometric Dicke Radiometer.doc
13. http://www.jupiterspacestation.org/software/Vlsr.html

Appendix - Post Processing for Linux

Information on setting up the OsmoCom rtl tools is given in Reference (6). Copy 'rafft' to your working Data directory. The programs are run in Linux terminals. The procedure for this is described below.
1. Set up your Data directory on the Desktop.
2. Open a terminal and change directory to the Data directory
3. To record data to .bin files, type on the command line… *rtl_sdr ./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 'Data' folder
4. Open a second terminal and change directory to the Data directory
5. To perform and average 256-point FFT spectra, type on the new terminal command line ….
   rafft capture1.bin capture1.txt 256
   the output capture1.txt file stored in the current directory can be input to Excel/Spreadsheet or any math cad program to compare pairs of load and antenna files to view hydrogen line spectrum.