Further Developments of an SDR Radio Telescope
Using FunCube Dongles and Spectrum Lab

3m Dish with 1420MHz Feed

ABSTRACT

The aim of this article is to set out the nature of the equipment configuration and software involved in setting to work a small 3m diameter amateur radio telescope using the FunCube Dongle Pro+ software defined radio receiver.

The antenna and head amplifier characteristics are discussed briefly, but for detail the reader is directed to previous publications.

Similarly, for information about the FunCube Dongle Pro and Pro+ software defined radio receivers, the reader is referred to previous publications and the FunCube Dongle website.

The body of the article deals with how Spectrum Lab software can be used to provide some advantages over a software package previously employed which cannot produce records from only selected parts of the measured spectrum. The ability to filter the received spectrum and divide it into a number of smaller bandwidth channels enables multiple band measurements to be made simultaneously. This provides some interference immunity against narrowband signals which may appear within the signal spectrum.

System noise and gain stability measurements are reported and give an insight as to what performance might be expected from a small SDR based radio telescope.

The typical ground noise to cold sky noise ratio is measured, suggesting how important it is for a practical telescope antenna to have minimal sidelobes and spillover.

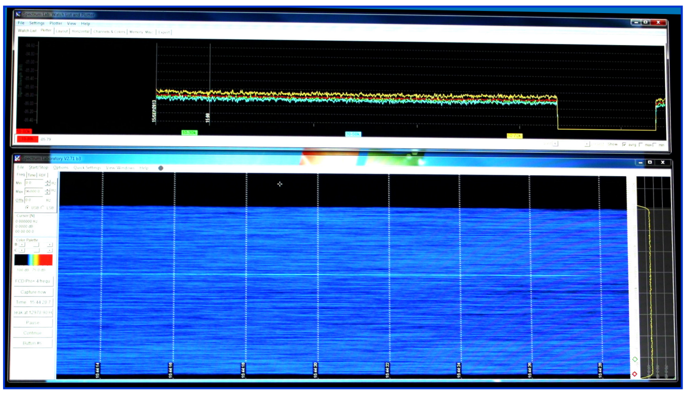
The signal level from a ‘quiet Sun’ is measured and compared with both ground and cold sky noise. The Sun can provide a very basic ‘point source’ calibration object and will be, by far the largest signal a telescope will see.

The H Line and synchrotron signal levels from the Cygnus arm of the Milky Way are measured and compared to system noise, ground noise, cold sky noise and Sun noise to show where they lie in the range of source signal strengths.

Finally the ‘clarity’ of the Galactic Plane signal is established by inspecting the ratio of the Hydrogen Line signal to the averaged noise fluctuations on it.

CONTENTS

FunCube Dongle Pro +



Spectrum Lab Software

1 Introduction to Developments

1.1 Previous Work

The initial work to develop a small radio telescope antenna and feed was carried out around 2011 and a paper describing the activity can be found on the author's website[1]. A short extract is given below as part of setting the scene for its use as a component of a radio telescope using software defined radio receiver in the form of the FunCube Dongle [2].

Construction of a 3 metre Amateur Radio Astronomy Dish Antenna for 1420MHz

Introduction

Requirement

The aim of constructing this antenna is to enable, at reasonable cost, an amateur radio astronomer to have a system capable of sufficient gain – and with a small enough beam-width – for the detection and mapping of the distribution of synchrotron and atomic hydrogen signals in the Milky Way.
Such goals represent a reasonable challenge for amateurs to undertake without incurring high expenditure or access to specialist microwave test equipment.

Technical considerations

The paper discusses the nature of parabolic reflectors including the diameter, focal length and F number best suited to radio astronomy applications. It considers the mounting and pointing of a substantial structure of 3m diameter and demonstrates how pointing errors can be determined.
Considerable attention is given to the development of suitable 'feeds' to be located at the focus of the dish and experimental methods are discussed showing how to understand and optimise the 'dish + feed' combination.
The technical details of very low noise figure 'head amplifiers' are given together with how these Low Noise Amplifiers (LNAs) and cable line driver amplifiers are employed and packaged within a temperature controlled environment.

Figure 1. 3m focal plane dish and 1420MHz feed

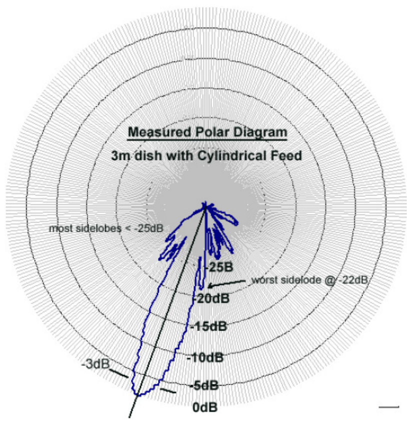


Figure 2 Dish polar diagram

The initial work on using the newly developed FunCube Dongle Pro (FCD) was carried out in 2011 with a short paper describing the activity posted on the British Astronomical Association (BAA) Radio Astronomy Group (RAG) website [3]. A short extract is produced below.

Experiments with a Software Defined Radio Telescope

Introduction
This paper describes initial experiments carried out to determine the performance of an amateur radio telescope employing a Software Defined Radio (SDR) receiver in place of a conventional communications receiver.

One motivation for conducting this experiment is the emergence of low cost, capable SDR components, that when connected to a suitable antenna and Low Noise Amplifier (LNA) might result in a low budget radio telescope that is well within the range of most people who wish to become amateur radio astronomers.

Figure 3. The Original FunCube Dongle Pro SDR

The FCD Pro is incorporated into the telescope system as indicated in Figure 4.

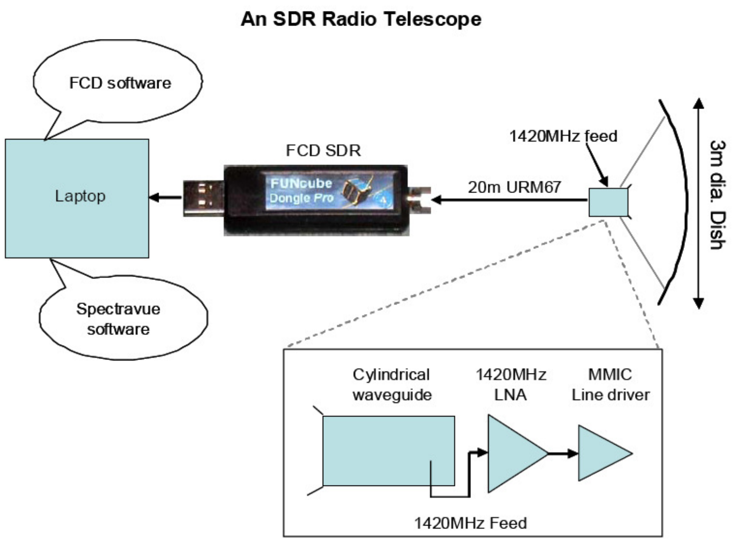


Figure 4. The 3m dish and feed connected to the FCD Pro

1.2 The system described above was used to demonstrate the ability to produce good signal to noise ratio detections across the Milky Way as shown in Figure 5.

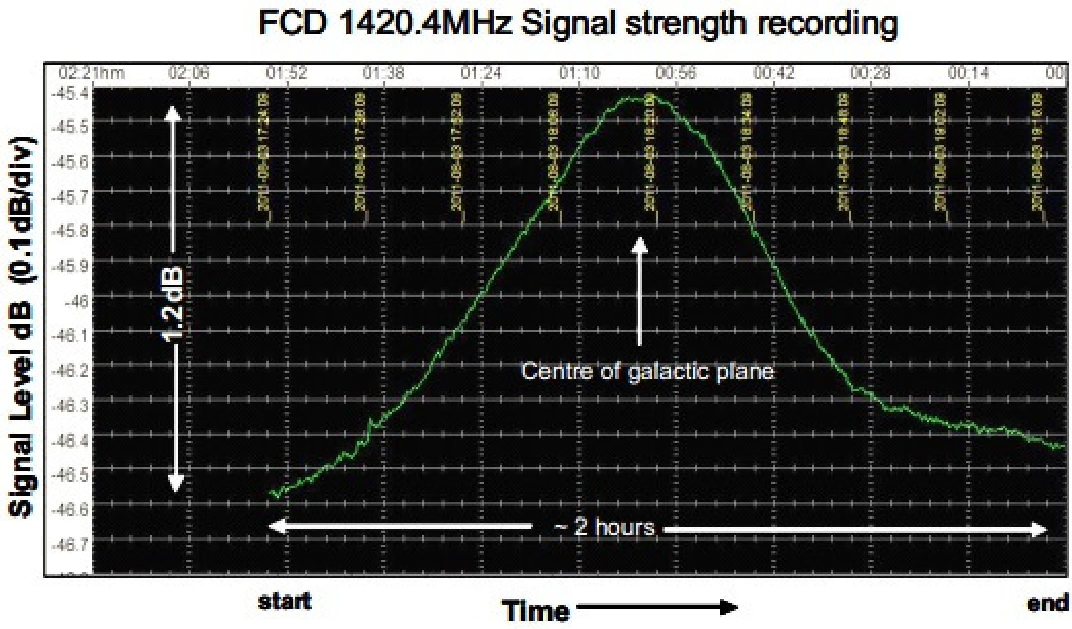


Figure 5-1. Graph of signal intensity at 1420.4MHz across plane of Milky Way

Since this initial work was published, it is known that several people around Europe have used the information to build similar telescopes based on the FCD SDR.

The software used to plot the signal strength from the FCDPro was SpectraVue. This is a useful software package with simple operation that can be used to capture and plot the signal level generated by a range of Software Defined Radios, including the FCD Pro and Pro+. However it has a limitation which causes some problems when recording radio telescope signals, if interference is present, or the zero frequency spike in the spectrum is not sufficiently nulled out. This is discussed in the next section.

2 Limitations of SpectraVue Software for Radio Telescope operation

2.1 The <continuum> function enables the software to plot a received signal level as a function of time as successive samples are taken. This is just what is required to produce plots of radio intensity across the sky, either when the antenna is driven, or in 'drift scan' mode', where the rotation of the Earth sweeps the antenna beam over the sky.

However it was found during various early measurements that the value of the plotted signal strength includes all signals across the 96 kHz band of the FCD Pro (+-48kHz). This includes any interference signals and the 'zero frequency spike' which may not be completely nulled out. See Figure 5 for an example of both effects.

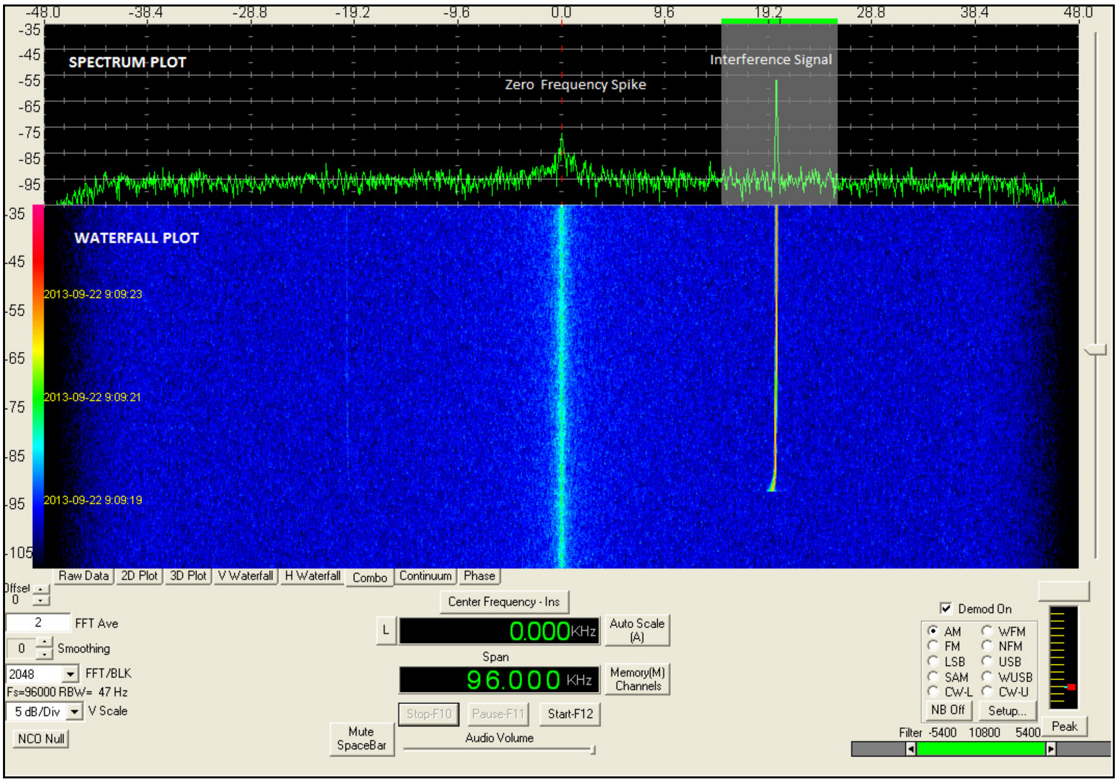


Figure 5-2. Example of SpectraVue Screen showing an interference signal & Zero Frequency Spike

The problem that arises is obvious, in that the amplitude of the astronomical signal – which is broad band noise – and the zero spike and any interference in the spectrum is added together (averaged) and results in a single amplitude measurement which is plotted.

This effect can be seen in figure 6 where the Zero Spike nulling routine in SpectraVue is activated. As the amplitude of the spike is reduced it affects the value of the 'continuum' data. The values are seen to drop as the spike is reduced.

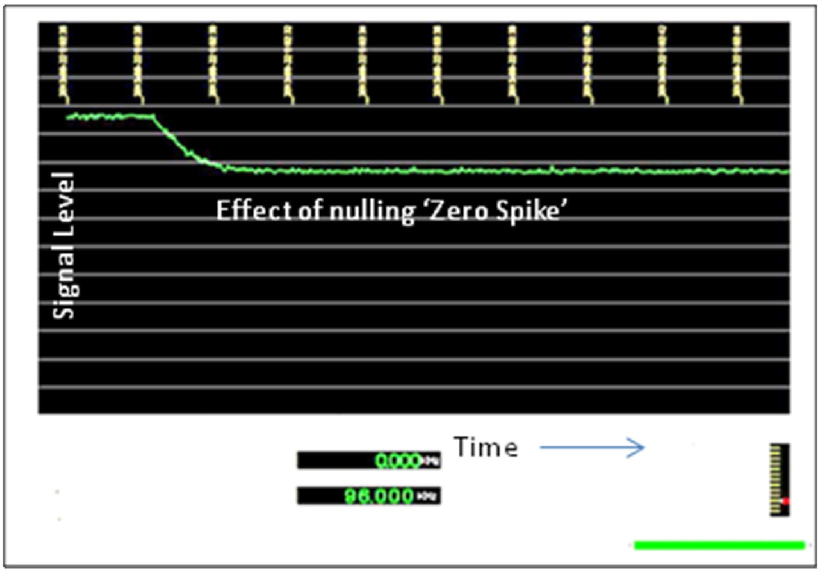


Figure 6. Showing the effect of reducing the Zero Spike in the Spectrum

Similarly, if a narrowband interference signal is present, this too affects the 'continuum' value as it includes an average of all Fourier frequency bins from zero to Fmax in the spectrum. This makes the radio astronomy measurements prone to upset during a measurement if interference arises.

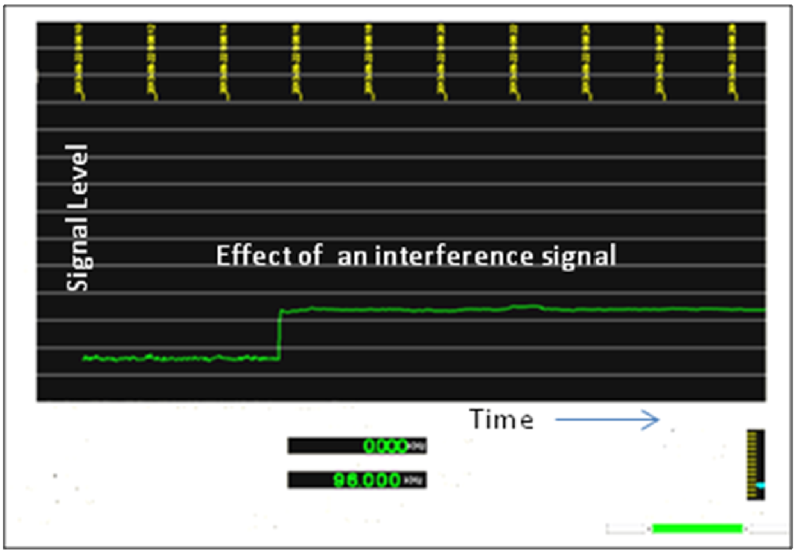


Figure 7. The effect of a narrowband interference signal on the 'Continuum' value

Of course, if the astronomical signal level is much greater than the value of the zero spike (so that the spike is swamped) and there is no interference, then the measurement is a good one. However these conditions cannot be guaranteed and the inability of SpectraVue to plot a 'continuum' signal level over a <u>nominated 'clean' part of the spectrum</u> is a disadvantage.

It would be very helpful to be able to define band limits in the spectrum to avoid including the Zero Spike and any ‘narrowish’ band interference.

It is possible to do this using Spectrum Lab software [5], as will be shown in the next section.

3 Advantages of Spectrum Lab Software

3.1 Spectrum Lab software is free and available on the internet at reference 5. It has been used for all kinds of spectrum analysis including audio / music analysis, Very Low Frequency (VLF) Ionospheric measurements and the detection and analysis of Meteor Radar reflections. In all the applications its versatility and wide range of programmable tools has proved very useful.

It is proposed to use Spectrum Lab as the key software element of the improved SDR Radio Telescope. What follows is an explanation of how this may be accomplished.

3.2 Spectrum Lab has a number of important features that are helpful in overcoming some of the limitations of SpectraVue. These include the 'frequency spectrum', 'waterfall plot' and' watch list' screens. The key facility however is the ability to define digital filters that operate on the Fourier Transform data enabling the filtering of unwanted signals within the SDR overall pass band. This enables the Zero Spike and any increased noise at the upper edge of the band (seen in the FCDPro+) to be eliminated, leaving a 'clean user defined pass band', within which the signal amplitude can be measured and plotted.

In addition the Watch List function allows the amplitude of signals in up to 20 defined bands (within the overall filtered band) to be separately plotted as a function of time. The plot may employ the 'average', peak' or 'noise' measurement functions of the signal within each band.

This functionality will be demonstrated in what follows.

3.3 The main screens of interest are shown below - they are:

- The Spectrum window
- The Waterfall plot
- The Filter window
- The Watch list setup screen
- The Watch list plot

Spectrum Window
The spectrum of the wide band signal from the FCD Pro (48kHz) or the later FCDPro+ (96kHz) can be displayed with various resolutions depending on the FFT settings and the amplitude range specified in <display settings (2)>. The window can be standalone – large screen, or combined with the Waterfall display. The spectrum plot can be used to identify any narrowband interference superimposed on the broad band astronomical source signal.

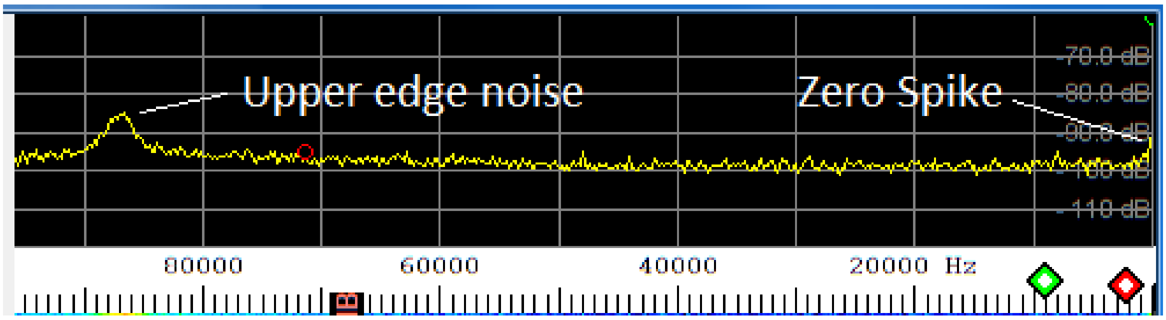


Figure 8. The Spectrum Window 96kHz wide (for FCD Pro+)

Waterfall Plot

In this application, the waterfall plot is of secondary importance to the spectrum display. It can be useful though, in viewing the changing signal amplitudes across the spectrum as time passes. If the scroll rate is sufficiently slow this will display the way the spectrum changes during the entire observation and will highlight the presence of any interference at particular frequencies and times.

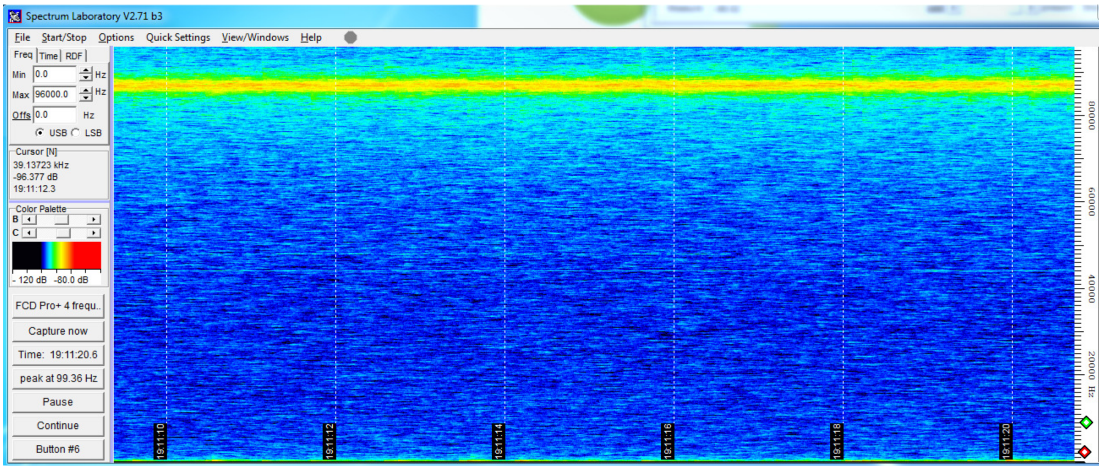


Figure 9. The Waterfall Plot Screen (Vertical Frequency Axis, Time Horizontal)

Filter Window

This is activated from the <View/ Windows> tab and enables the user to define sharp sided filters which can be used to remove the Zero frequency spike and the increased noise at the upper band edge. This leaves a ‘clean spectrum’ which can be further segmented in the ‘Watch List’ setup to deliver a set of signal amplitude plots in a number of narrow bands.

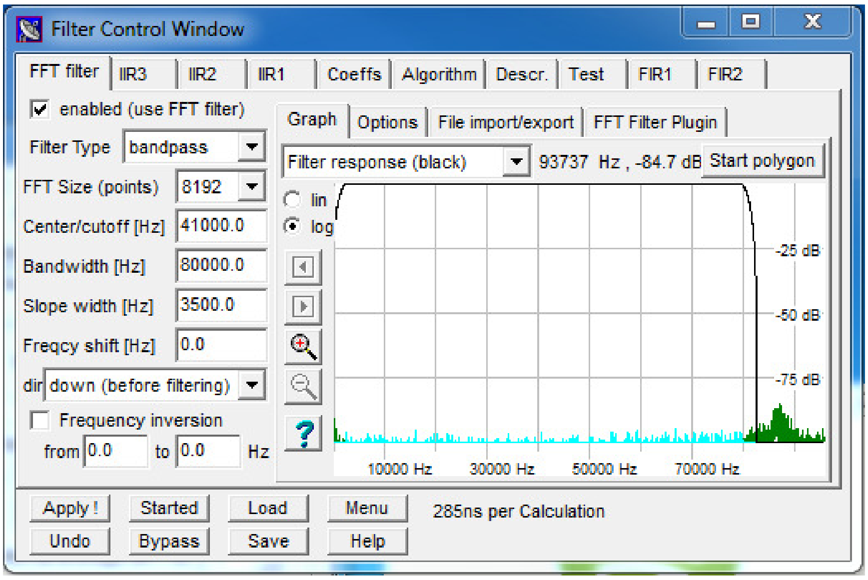


Figure 10. The Filter Control Window (sets the overall passband)

Watch List setup Window

This takes the form of a spreadsheet in which the various frequency bands can be defined. It also enables average, peak or noise calculations to be made returning a value for the signal amplitude in the specified band. This leads to the possibility of making several parallel measurements of the astronomical signal amplitude in adjacent bands and provides some measurement redundancy. If interference arises in a particular segment of the spectrum, the measurements made in adjacent bands may be 'clean' and can be used in the subsequent data processing to provide the final result.

There are also parameters in the set up window to set the scale limits for the watch list plot window.

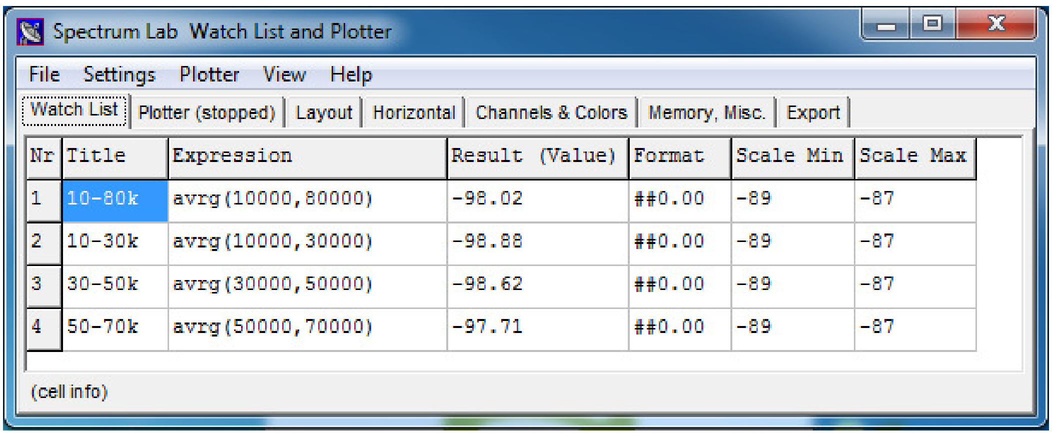


Figure 11 The Watch List setup Window (showing amplitude averages in 4 bands)

Watch List Plot Window

This simply displays the multiple traces of signal strength in each of the bands defined in the Watch List setup window. It enables a real time view of the progress of the measurement as the astronomical source passes through the antenna beam. The output data is accessed through the <File> tab in the Watch List window by selecting the <Save as Text File> which produces a .csv text file capable of being imported into Microsoft Excel for example.

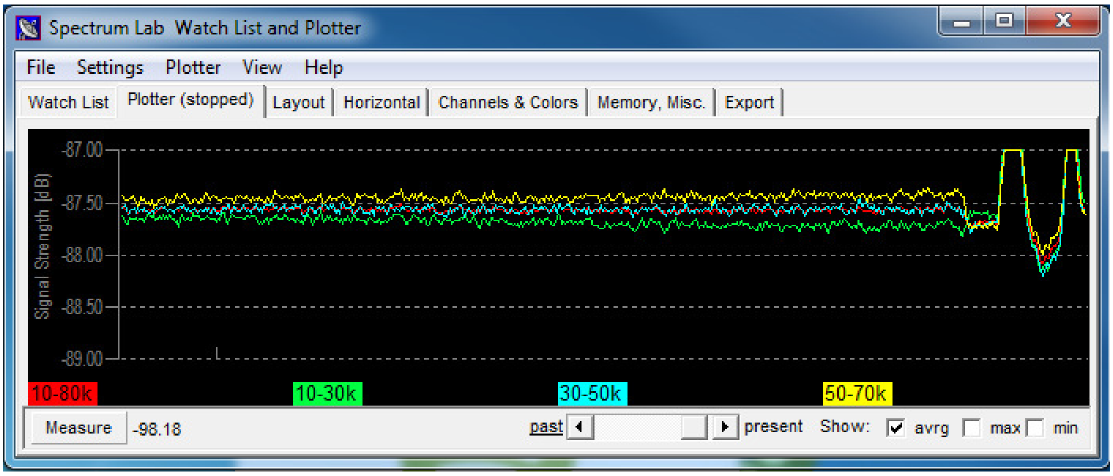


Figure 12. Watch List Plot Window (showing 4 bands as different coloured traces)

Spectrum Lab can be used with any ‘sound card’ type device including both the FCD Pro and the later FCD Pro+ as shown below in Figure 13.

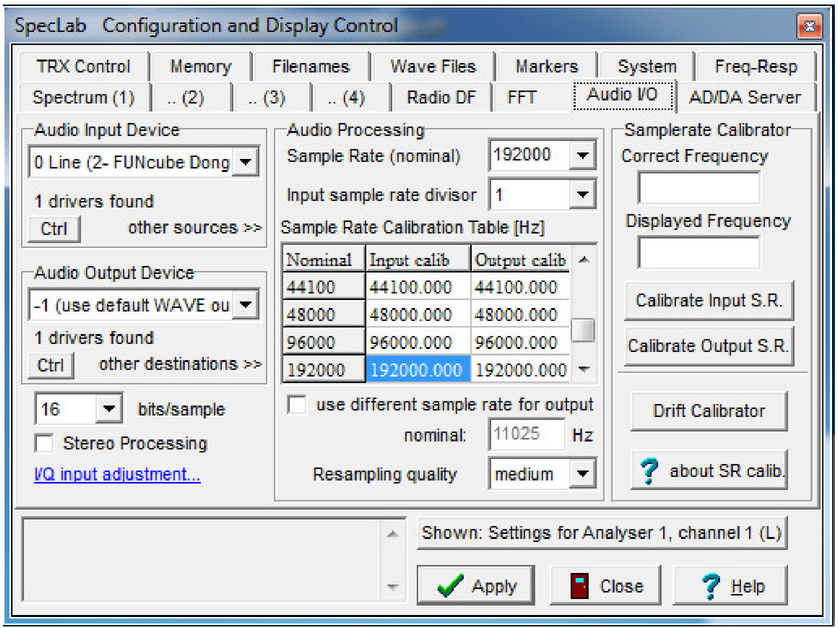


Figure 13. Audio input Device selection Window

In what follows the experiments are conducted using the more recent device which has a higher (96 kHz wide) bandwidth. The configuration of Spectrum Lab and the FCD Pro+ is given in Appendix A.

3.4 Spectrum Lab as a multi channel Receiver

Figure 14 shows the block functional diagram of Spectrum Lab configured as a multi channel radio astronomy receiver. It will measure the received noise power in 4 bandwidths – 10-30 kHz, 30-50 kHz, 50-70 kHz and the overall band 10-80 kHz.

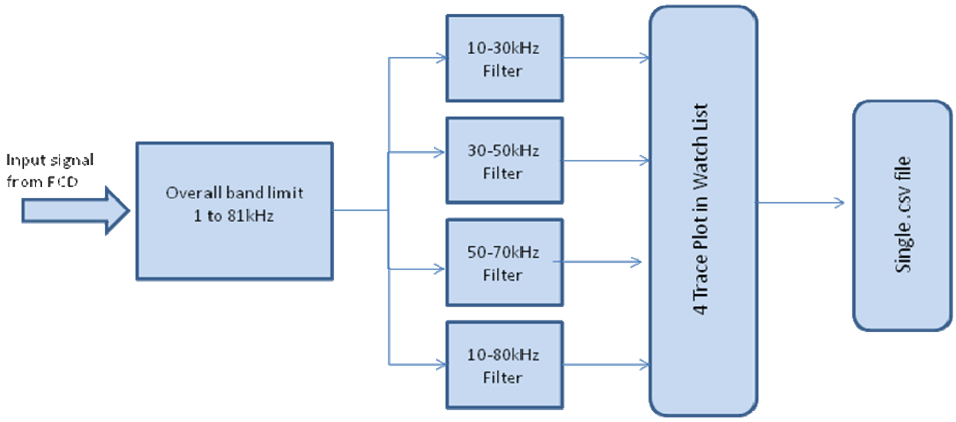


Figure 14. The Functional Block Diagram of Configured Spectrum Lab

The main Filter Window enables both the zero spike and the upper edge band noise peak to be removed from the data, resulting in only the wanted astronomical source noise being measured. The Filter function is shown in figure 15 as a red line.

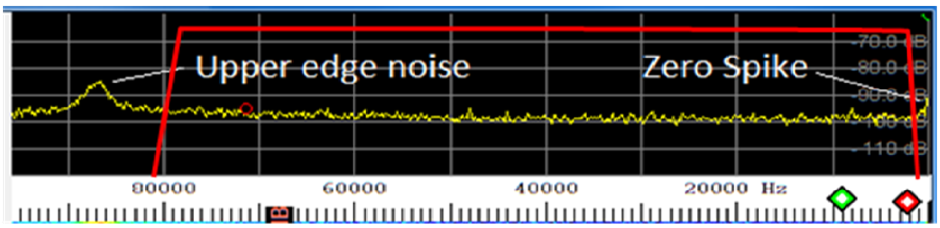


Figure 15. Application of main 1 to 81kHz Filter

The final set of 'filters' is configured in the Watch List setup window as shown in figure 16.

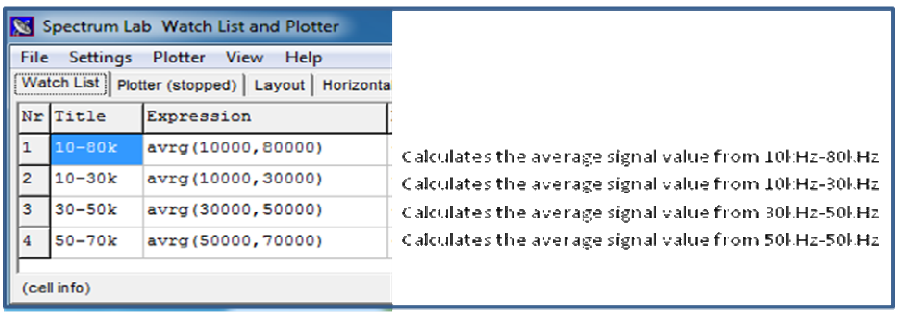


Figure 16 The final four Filters defined in the Watch List Setup

4 Stability and Noise Experiments with FCDPro+

4.1 With the ability to use Spectrum Lab as the main recording and analysis tool, it was possible to conduct a number of experiments to determine the noise level and gain stability of the FCDPro+ device. These assessments are important if we are to have confidence in using this SDR device as the central element of our radio telescope.

If the telescope is to be used as a transit instrument, then the requirement for long term gain stability is high, as each scan may last for up to 17 – 20 hours if radio sky mapping is the object of the exercise.

The receiver noise must obviously be as low as possible to achieve the greatest sensitivity, but this noise level must also be stable over long time periods if it is not to confuse the astronomical measurement results.

We therefore need to establish by experiment the performance of several aspects of telescope operation, including:

- FCD noise output level and stability
- The FCD gain stability
- The ratio of the antenna & feed preamplifier noise to the FCD noise level
- The ratio of ‘hot’ ground noise to ‘cold’ sky noise (System noise)
- Typical signal level from a ‘quiet Sun’.
- The ratio of System noise to typical astronomical source noise (Milky Way)

With these data we will have established the performance capability of the SDR based radio telescope. In what follows, the measurement examples given, are for the authors 3m dish telescope and the FCD Pro+ receiver.

4.2 FCD Pro+ Noise Output Level & Stability
The FCD Pro+ noise level was measured with a 50 ohm sma load on the device input. The measurement configuration is shown in Figure 17. The software configuration was as in Appendix A

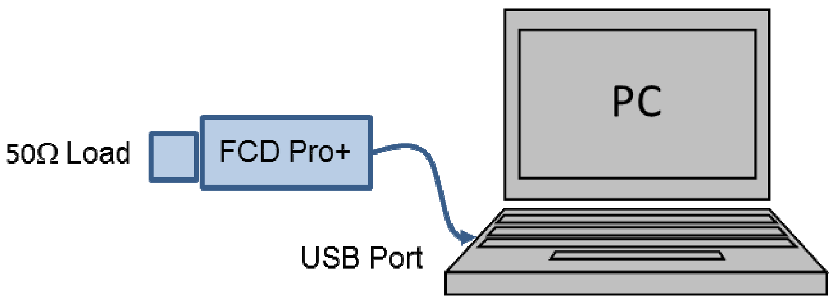


Figure 17. FCD Pro+ Internal Noise Test Configuration

The PC was running Spectrum Lab with primary filter bandwidth from 1 kHz to 81 kHz (cutting out the Zero Spike and the upper band edge noise peak).

The Watch List filters were set at:
10-30 kHz, 30-50 kHz, 50-70 kHz and an overall measurement of 10-80 kHz.

During the first hour or so after powering up the FCD Pro+ via its USB connector, it was found that the device did not produce a stable noise output. Several small 'glitches' were observed with noise levels changing by around 0.2dB as shown in figure 18.

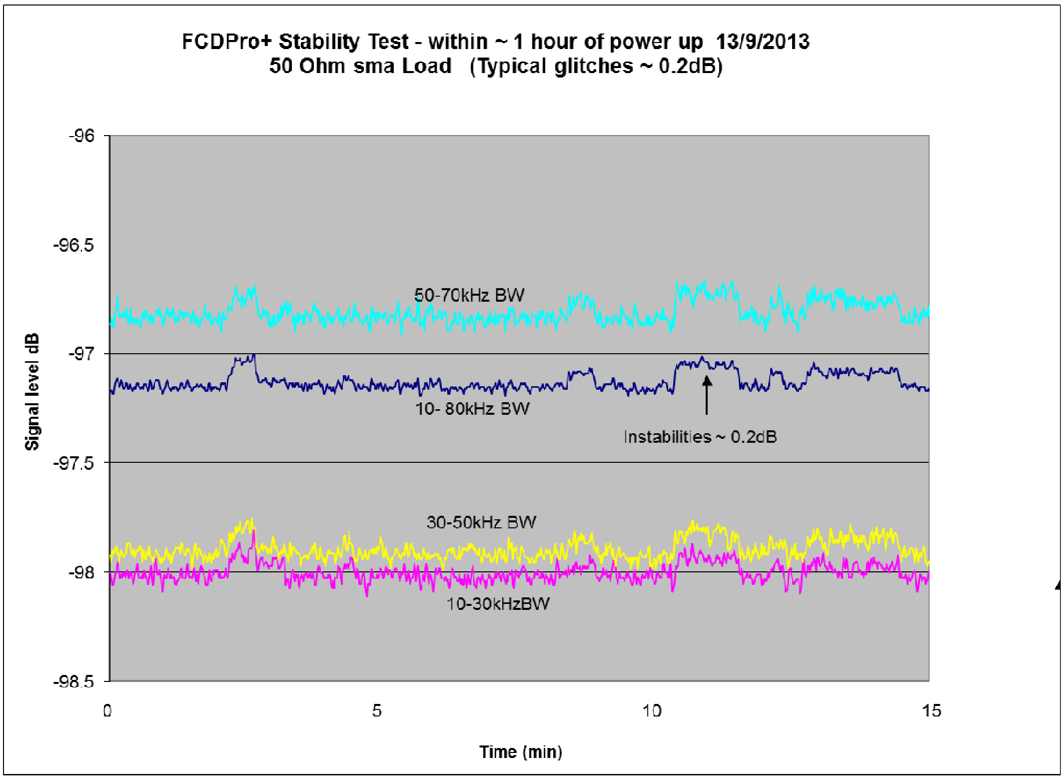


Figure 18. FCD Pro+ Noise level and Stability

The fact that the traces are not coincident in amplitude demonstrates that the output noise spectrum is not 'flat' across the 0 to 96 kHz FDC Pro+ band.

After 1 hour, these 'glitches' ceased. It is not possible to definitely attribute the 'glitches' to the FCD Pro+. It may be that these are generated in the sma load or possibly in the PC hardware – however this thought to be unlikely.
It is therefore recommended that potential users of the FCD check for internal noise stability during device warm up, before commencing any 'live astronomical measurements.

4.3 FCD Gain Stability

The equipment was configured as in figure 19. The signal source was a stable wide band random noise generator. See Appendix A. The noise output was band limited to around the test frequency of 800MHz to ensure that the FCD Pro+ was not saturated and in compression. (Linearity tests were conducted to confirm this).
All items had been powered up for more than 1 hour to achieve thermal stability prior to conducting this test.

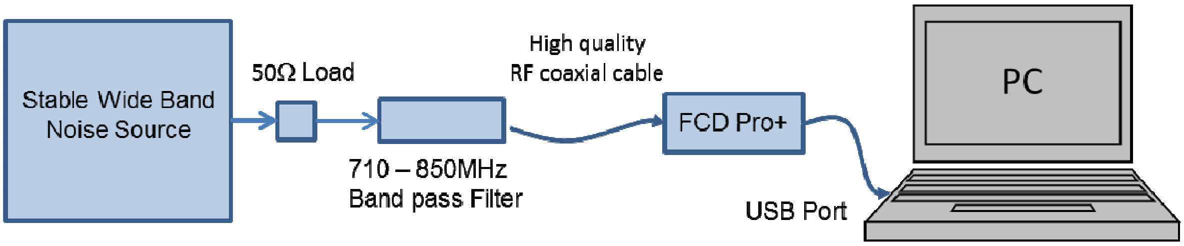


Figure 19. Measurement configuration for FCD Pro+ Gain Stability Test

The results in figure 20 show that the long term drift in gain is better than 0.05dB over more than three hours. By signal averaging the noise level can be reduced to better than +-0.02dB (black traces). This sets the amplitude resolution for any astronomical measurement made with the FCD Pro+ device.

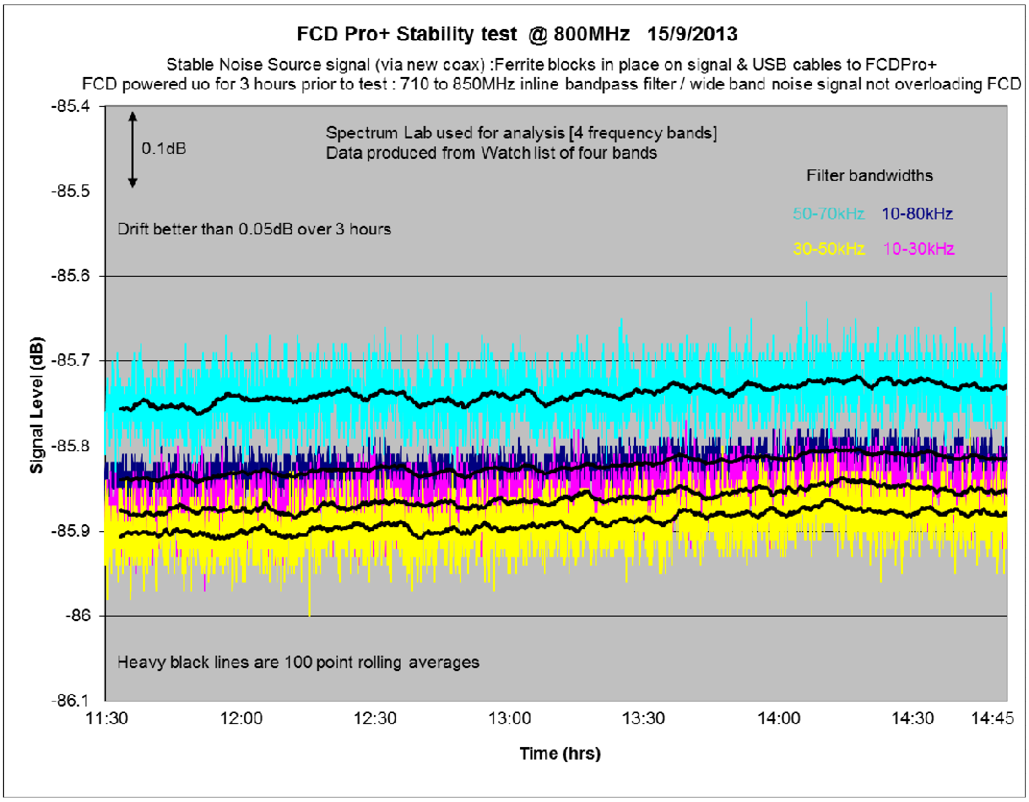


Figure 20 Stability of FCD Pro+ with stable input noise signal 12dB above FCD internal noise level

4.4 Ratio of the Antenna & Feed Preamplifier Noise to the FCD noise level

It is important to determine that the signal level (noise) from the antenna / feed/ preamplifier is significantly greater than FCD Pro+ basic noise level. This will ensure that the measured signal levels are due to signals from the antenna and not the FCD itself. The noise level and gain of the preamplifier (head amplifier) must be designed to achieve this. In the case of the author's equipment the head amplifier gain is 44dB and the front end noise figure is 0.3dB at 1420MHz.
The graph showing the ratio of head amplifier noise to FCD noise as 11.7dB, is given in figure 21.

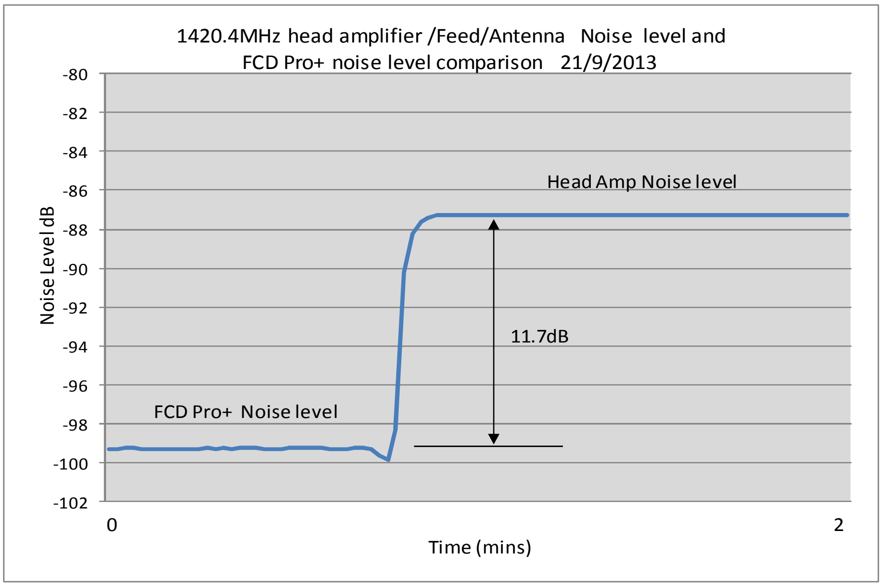


Figure 21. Ratio of Head amplifier + Feed + Antenna noise to FCD Pro+ noise

4.5 Ground to 'Cold Sky' noise Measurement

The next step in setting to work the SDR radio telescope is to measure the difference between ground noise – when the antenna is pointed at the ground - and when it is pointed up at the 'cold sky'. This gives an indication of the maximum signal to noise ratio that will be seen when making astronomical measurements. The ground is at a temperature of ~ 20^{0}C or 290^{0}K and the cold sky is the lowest object temperature available for testing.

The cold sky is taken to be a region of sky well away from the Sun / Moon etc and in the region of the Galactic Pole, well removed from the plane of the Milky Way.

Most astronomical measurements that can be made with the system will lie between the hot ground and the cold sky limits. The measurement is made by driving the antenna elevation from horizontal to ~+70^0 in the direction of the Galactic pole. The resulting measurement is shown in figure 22.

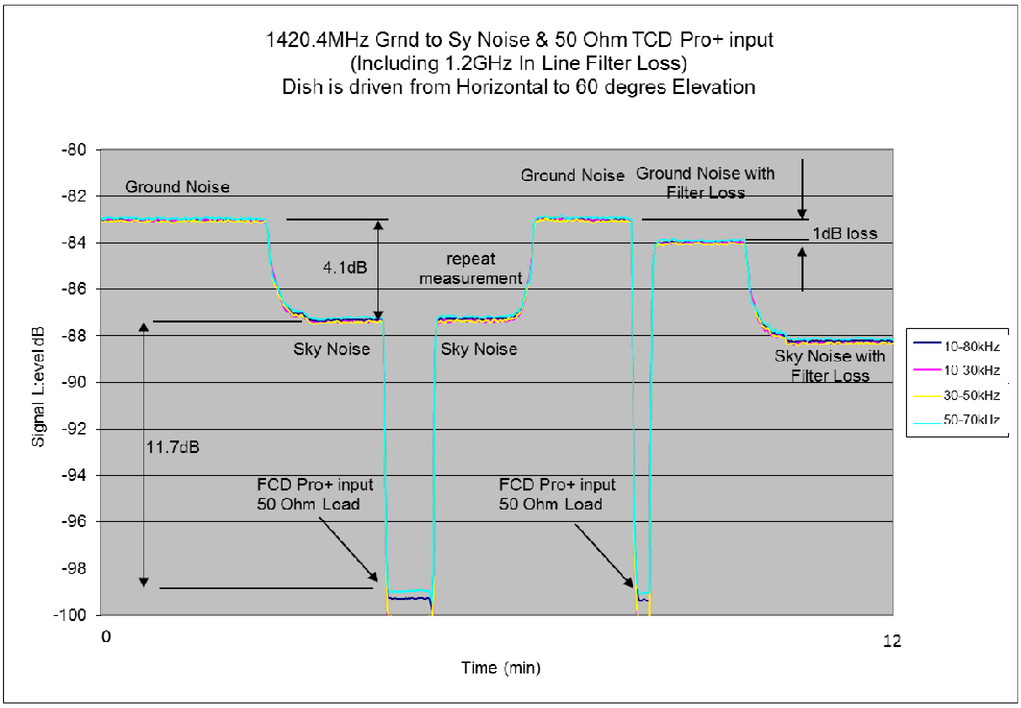


Figure 22. Ground to Cold Sky Noise measurement

On the left hand side of this graph a difference of 4.1dB can be seen between the warm ground (290^0K) and the cold sky. The ratio of cold sky noise (system noise) to FCD noise is measured as 11.7dB. The measurement is then repeated in reverse order.

Following this, a 1200MHz high pass filter is inserted into the signal path before the FCD Pro+ to make sure that there are no low frequency interfering signals, or that the accumulation of broad band noise below 1200MHz is driving the FCD towards non-linearity. The result shows the insertion loss of the filter as 1 dB, but the ground to sky ratio remains the same, ensuring that the FCD is not near saturation.

The graphs shown above were produced by exporting the Watch List data to a .csv text file using the <Export to Text File> function under the <File> tab on the Watch List Window. The actual Spectrum Lab real time display is shown in Figure 23. This real time data viewing capability of the software is very useful during measurements, as it enables the existence of interference or spurious data to be detected and the run aborted without wasting time.

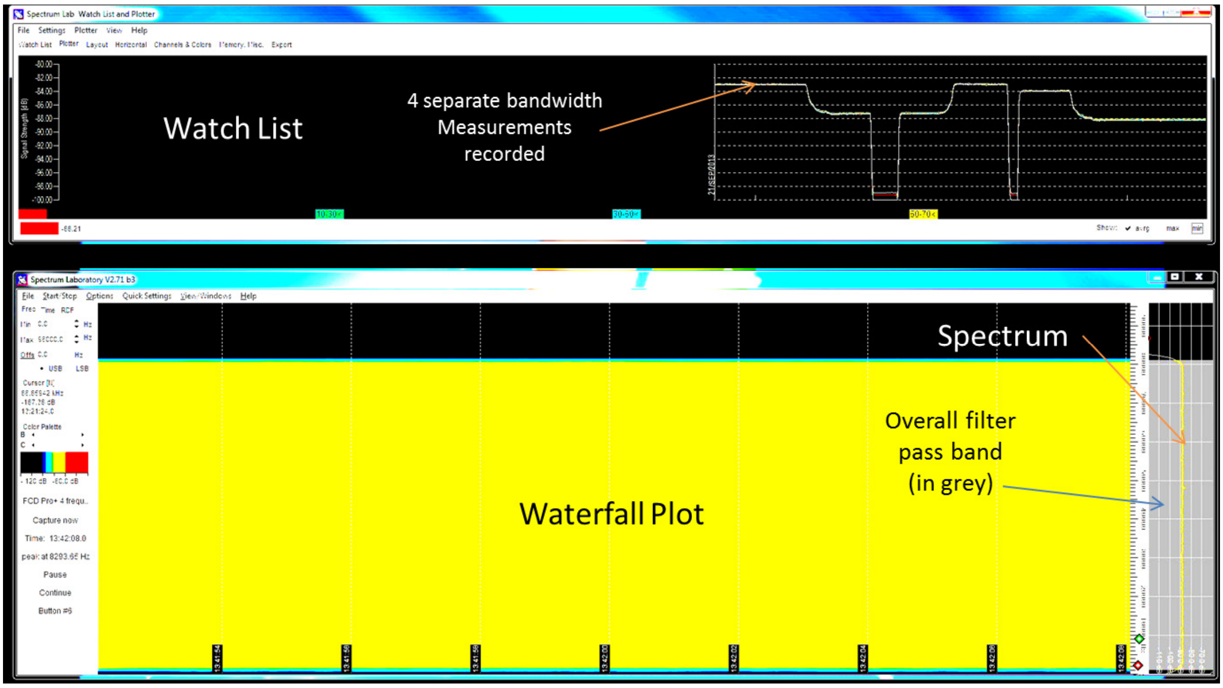


Figure 23. The Spectrum Lab 'real time' view of the measurement data

5 Measurement of Sun & Milky Way Cygnus Spiral Arm

5.1 Initial measurement of Astronomical Objects

Having set to work and 'calibrated' the system using Spectrum Lab we are now in a position to measure some astronomical objects. The Sun is the obvious first choice as it produces a very strong signal. The quiet Sun generates radio noise with a thermal spectrum whereas the disturbed Sun produces a much stronger signal but with a non-thermal synchrotron type spectrum. See figures 24 and 25.

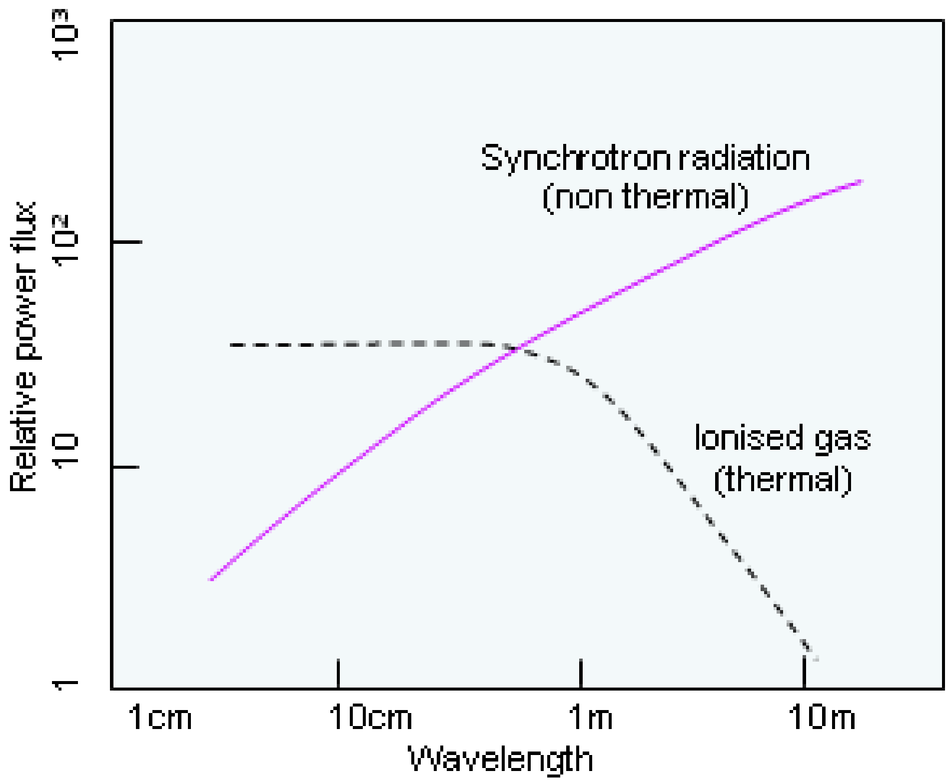


Figure 24. Comparison of Thermal and non-thermal radio spectra

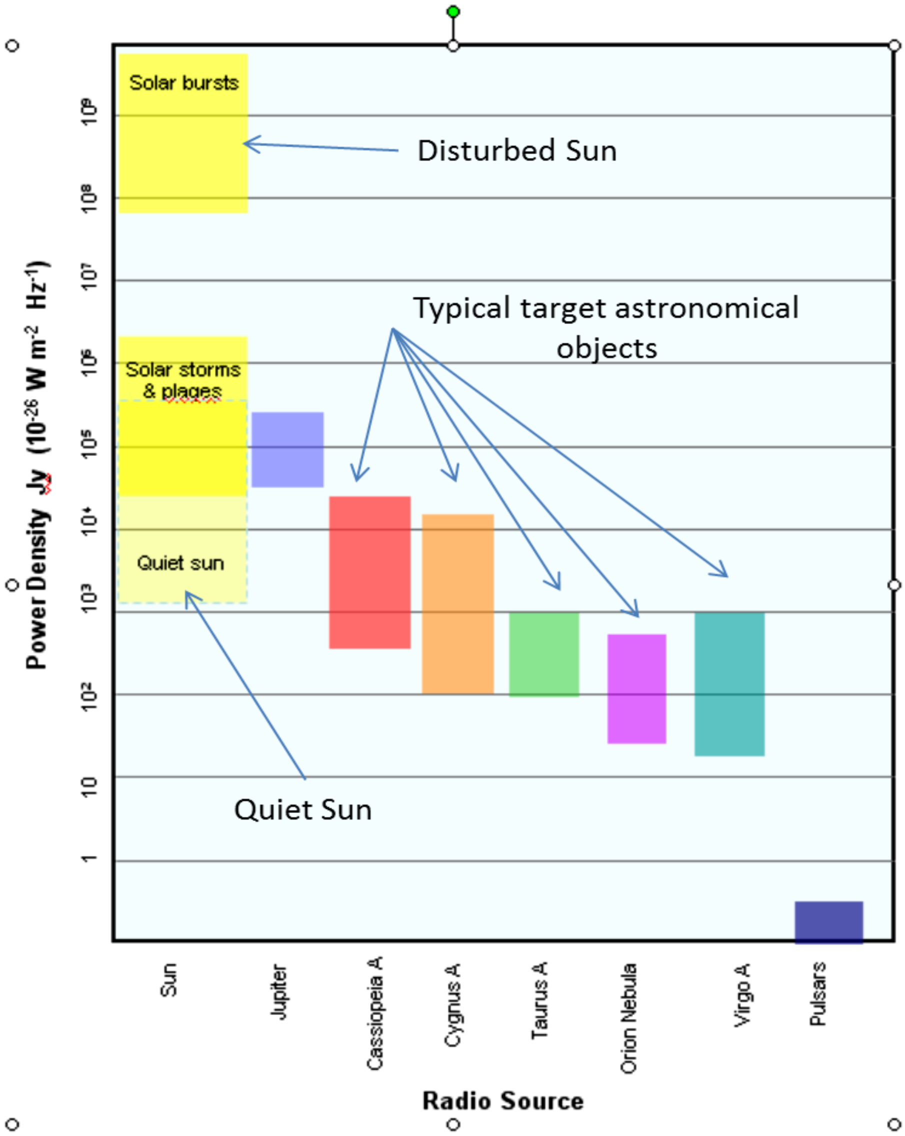


Figure 25. *Comparison of Radio signal strengths of astronomical objects*

We can see that the 'quiet Sun' is a strong source and that most of the other sources that might be observed by amateur radio astronomers are weaker than this.

Figure 25 requires a few words of explanation to understand its importance to the expectations of amateur radio astronomers as to what they may be able to detect using a system comprising of a 3m diameter dish / a suitable cylindrical waveguide feed, a 0.3dB noise figure head amplifier and an FCDPro+ SDR receiver.

The intensity of sources is measured in $W/m^2/Hz$ (a measurement of power spectral density) where 10^{-26} $W/m^2/Hz$ is known as 1 Jansky. (The vertical colour bars for each source accommodate the variation of the source spectrum over a range of frequencies – as indicated in figure 24). The source known as Virgo A or Messier 87 (M87) for example can be seen to be about 2 or more orders of magnitude weaker than the quiet Sun.

Therefore measuring the quiet Sun signal strength gives a datum point for the telescope system from which the system signal to noise ratios can be predicted for the other weaker sources.

5.2 Measurement of Signal from the Quiet Sun

The signal strength from a quiet Sun was made at ~13:00 BST on 27/9/13. The motorised telescope beam was slowly scanned across the Sun and the data recorded using Spectrum Lab configured as previously described. The result is shown in figure 26.

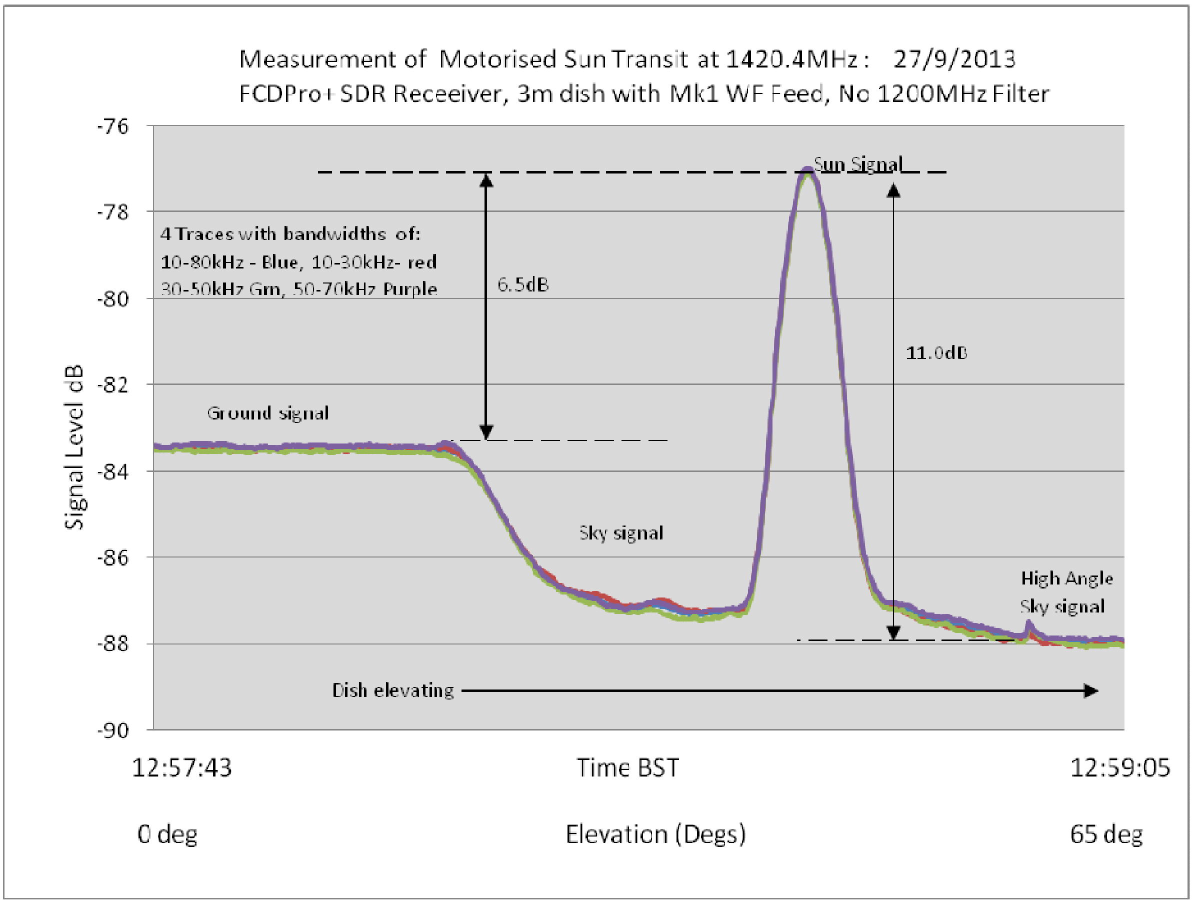


Figure 26. Measurement of Quiet Sun Signal Strength

We see that the peak signal strength obtained with the 3m diameter dish is ~ 11dB above system noise*. The Sun noise is also 6.5dB above the ground noise with the dish at 0^0 elevation. This Sun signal is the strongest signal any amateur radio astronomer is likely to measure – other than during Sun storms.

*System noise here is taken to be the cold sky noise level at 65^0 elevation.

5.3 Drift Scan Measurement of Milky Way Galactic Plane Hydrogen line

The FCD Pro+ was tuned to 1420.4MHz, which is the 'at rest' frequency of the atomic hydrogen emission line. The FCD receiver bandwidth is 80kHz which is much less than the spectrum spread from Doppler shifts due to the velocity of the galactic spiral arms. Typically the signals are spread over approximately 1420.4MHz +- 500kHz (see figure 27), thus the FCD will not always be tuned to the Doppler shifted H line spectral maximum as the dish beam crosses the galactic plane during a drift scan.

The resulting measurement may not therefore always show the strongest signal. We may therefore expect the full signal from the H Line spectral maximum to be somewhat greater than that indicted in this test measurement.

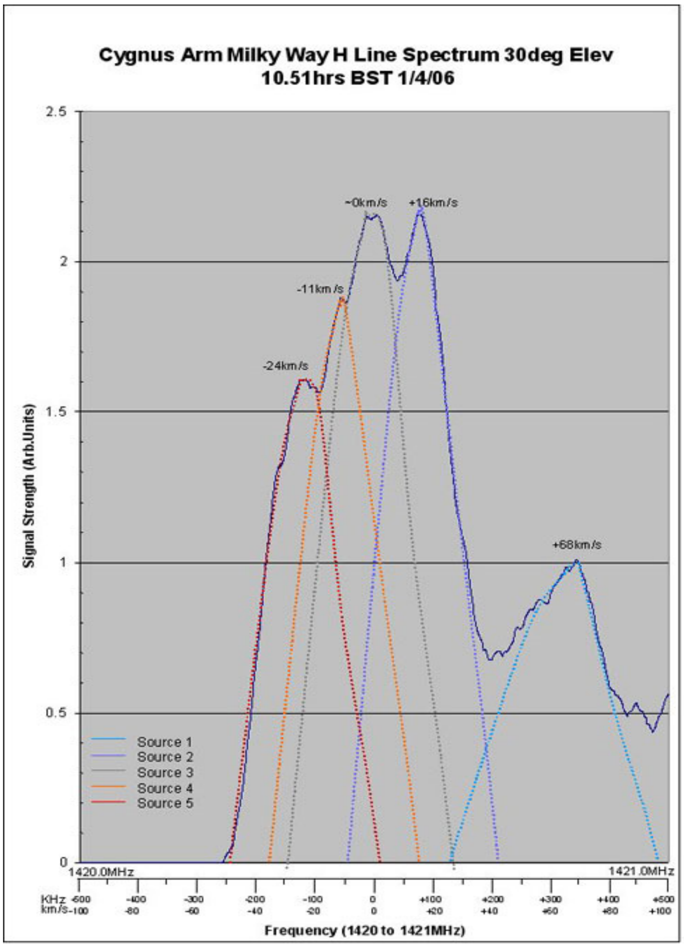


Figure 27. Typical Doppler shifter Hydrogen Line Spectral Components

The telescope was set up for a drift scan across the plane of the Milky Way through the local Cygnus - Orion spiral arm as indicated in the plot in figure 28 using the Radio Eyes [6] celestial navigation software.

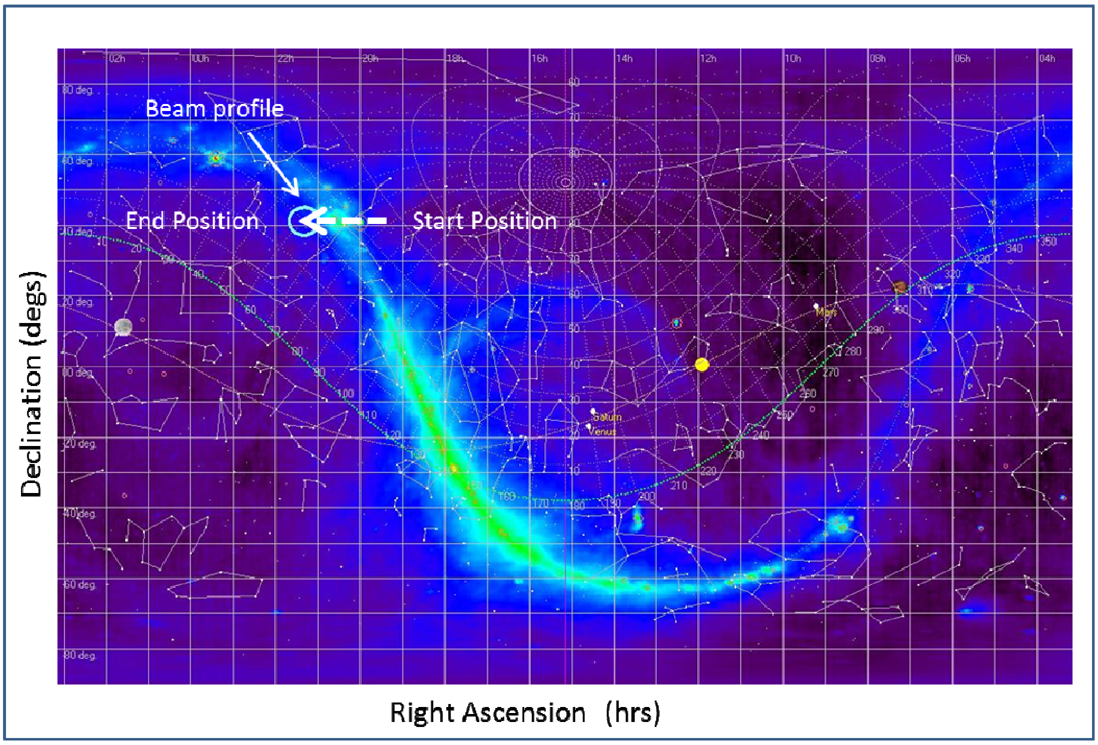


Figure 28. Location of Drift Scan thought Milky Way galactic Plane

The resulting measurement is shown in figure 29.

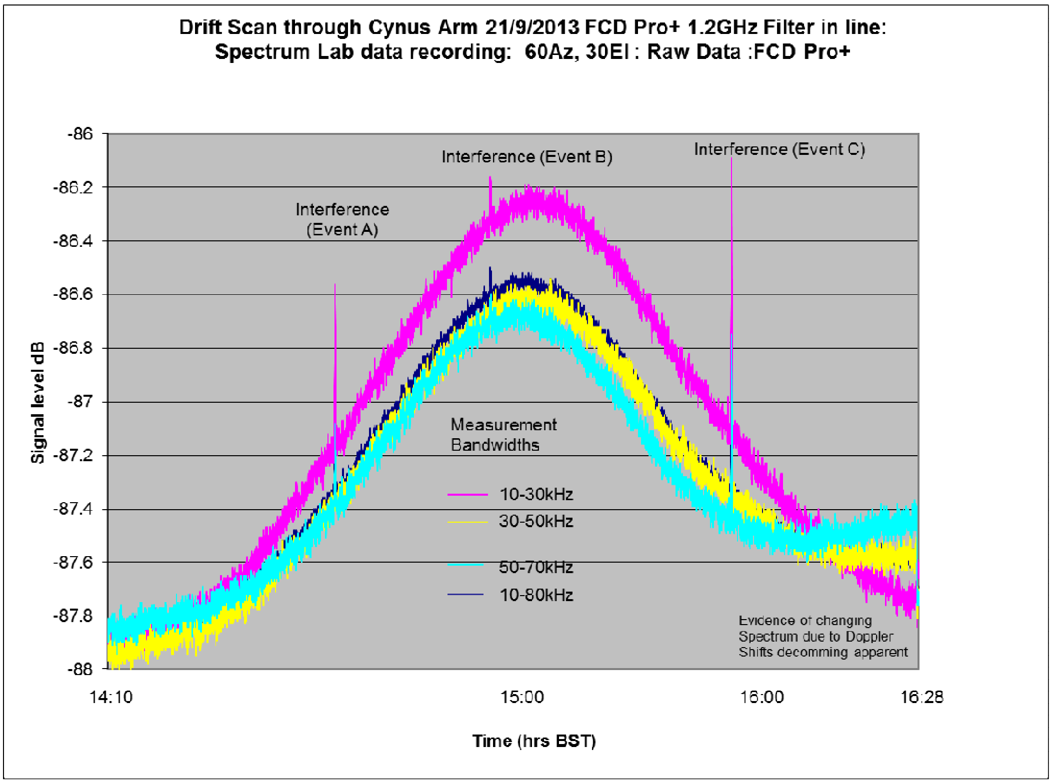


Figure 29. Signal Intensity during Drift Scan through Cygnus Spiral Arm

This graph of unprocessed raw data has a number of interesting features:

- The galactic plane is clearly defined
- The different filter bands show similar results except at the end of the trace. Here the amplitudes of the different filtered signals differ from one another indicating that the H Line spectrum is beginning to change as the beam moves out of the spiral arm.
- Three interference spikes are captured. However the level of the interference is not the same in all filer bands. This is shown in more detail in figure 30 for the first interference spike denoted Event A.

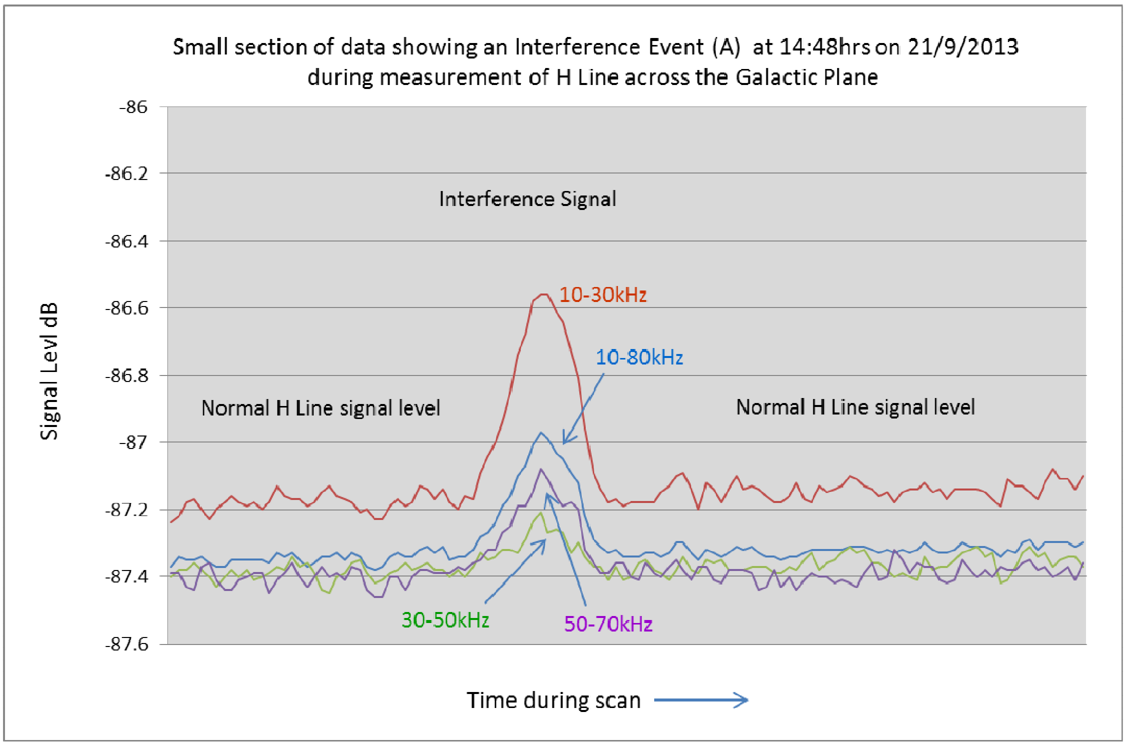


Figure 30. Detail of interference spike (Event A)

The graph shows that the interference was the smallest for the mid band filter between 30 to 50 kHz and greatest for the filter band closest to the 'Zero Frequency' of 1420.04MHz. The plot demonstrates the value of being able to, in essence, make 4 separate measurement of the Milky Way at the same time and be able to select if required, the data with the least interference level.

Even the 10-30 KHz data with the largest interference spikes can be processed to remove the artefacts using an Excel spread sheet. The processed data is displayed in figure 31. The light blue trace is raw data with the interference removed – and the thick blue line is filtered version employing 20 point running mean smoothing.

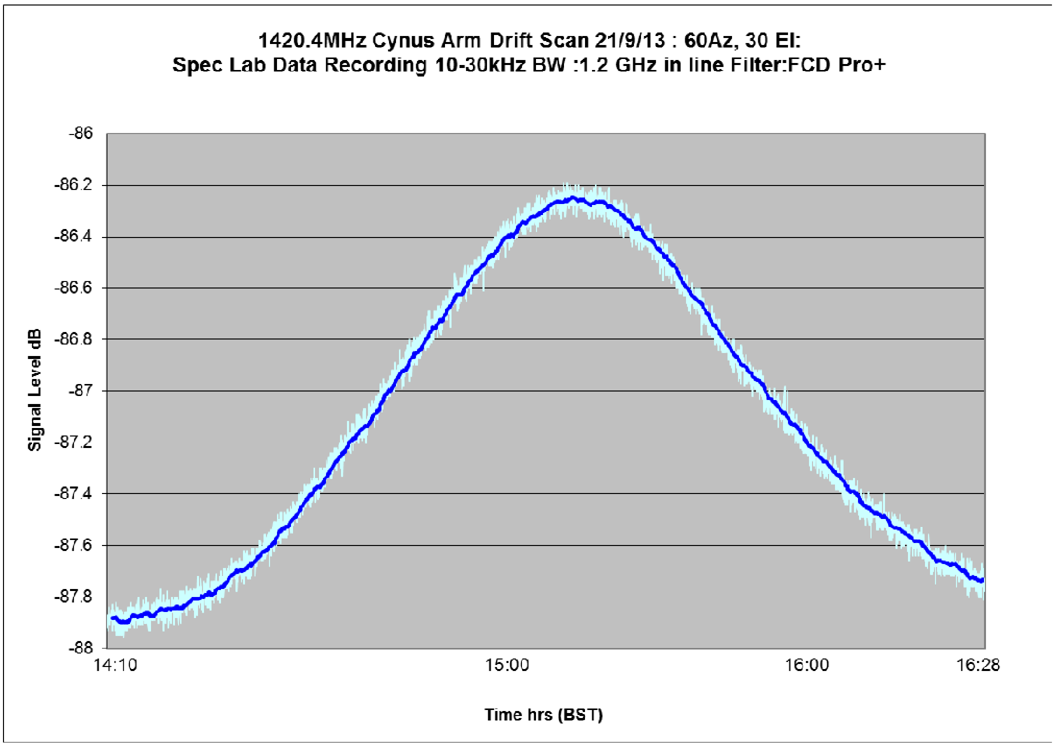


Figure 31. 10-30 kHz Filtered data across Cygnus Arm of the Galactic Plane

The signal to noise ratio can be further improved by operating on the data with the Excel averaging function with a 100 point average. As data is recorded every 1 second this represents an average over 1minute and forty seconds.

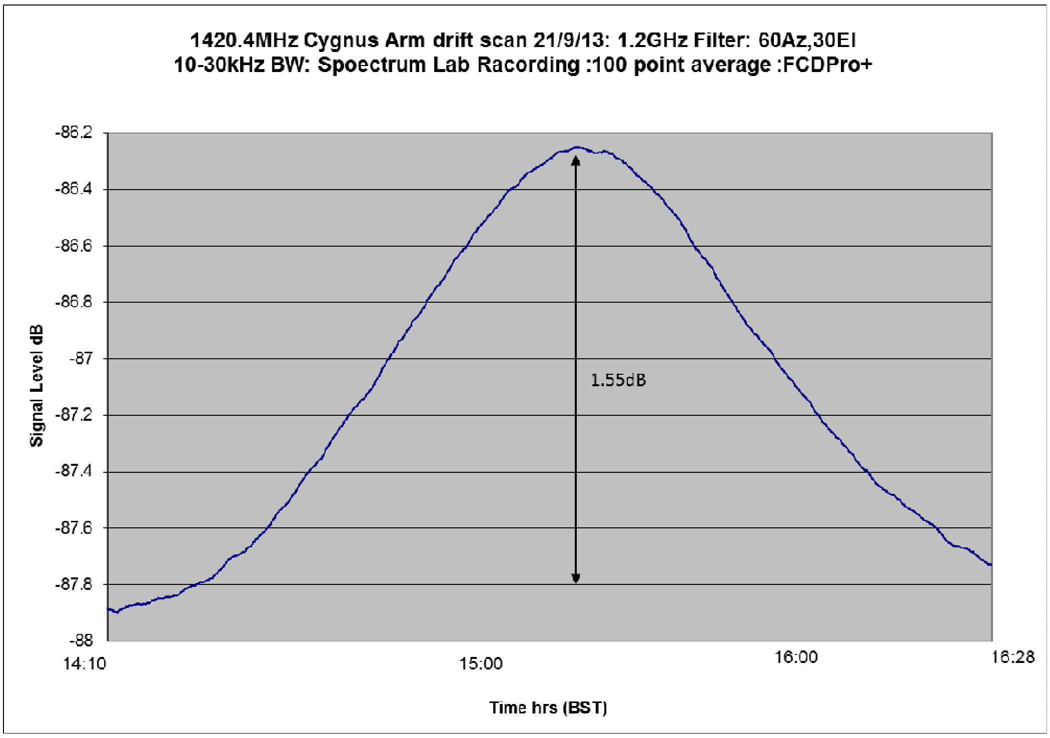


Figure 32. 100 second average data improving Signal to Noise Ratio

5.4 Motor Driven dish scan of H Line Milky Way Cygnus Spiral arm

The telescope elevation drive motor can be used to collect signal strength data at 1420.4MHz across the Cygnus Spiral Arm much faster than is possible with a drift scan. One aim of such an experiment is to determine to what extent the form and signal to noise ratio of the measurement is compromised by a rapid scan through the galactic plane feature. The telescope was driven at its fastest rate – crossing the galactic plane in just 30 seconds.

The result of an upward scan, followed by a downward scan, which continues down to the horizontal to measure the ground noise relative to the signal from the Galactic Plane, is shown in figure 33.

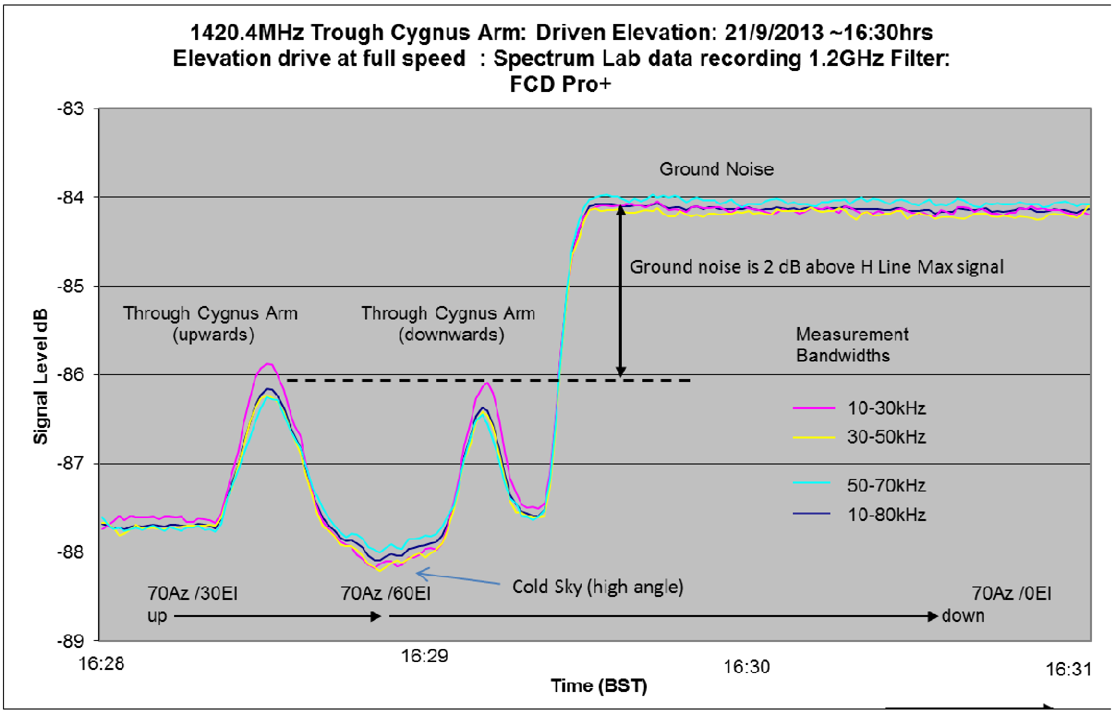


Figure 33. Rapid Motor driven Elevation Scan through Cygnus Arm of Galactic Plane

The ratio of the maximum signal detected during the passage of the beam across the Galactic Plane to the ground noise signal is 2 dB. This shows how important it is to only measure astronomical sources at reasonably high elevations, if the ground noise is not to enter the main beam and swamp the wanted signal.

This also illustrates the desirability for any antenna used for radio astronomy to have low sidelobes and spill over in order to avoid picking up the emissions from the hot ground.
Generally it is not advisable to use elevations less than 30^0 above the horizon when using a small 3m diameter focal plane dish with a main 3dB beamwidth of ~ 8^0.

The peak signal through the Galactic Plane is measured as being ~1.6dB above the level outside the plane. This is quite comparable with the figure arrived at from the drift scan, showing that there is no loss of signal due to the more rapid motor driven measurement.

The motor driven measurement of signal strength through the Cygnus Spiral Arm is shown in figure 34.

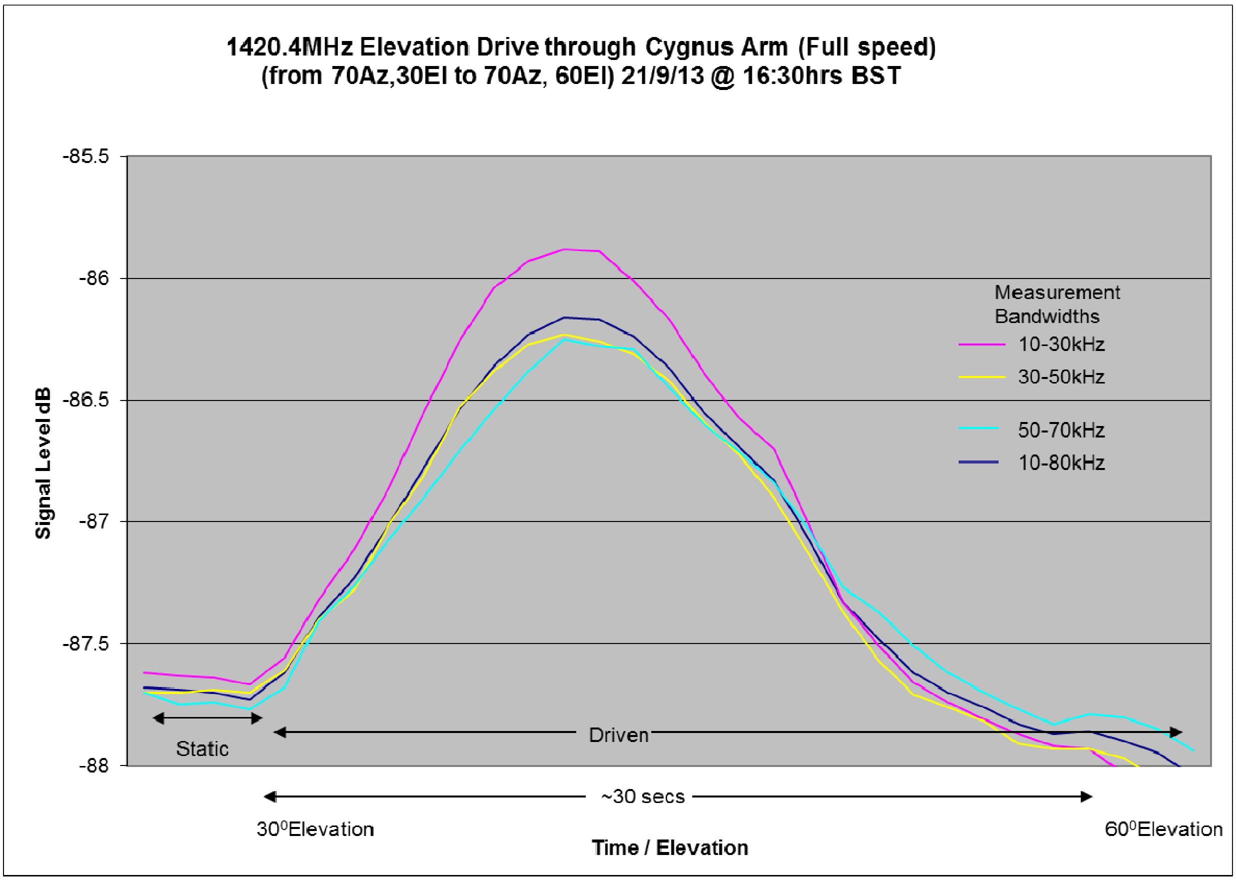


Figure 34. Motor driven measurement ACROSS Cygnus Spiral Arm

5.5 Measurement of Milky Way Synchrotron Radiation

Synchrotron radiation is produced by charged particles (usually electrons) moving at relativistic speeds (ie. close to the speed of light) spiralling in a magnetic field – see figure 35. These conditions exist widely in the galaxy and radiation is generated over a broad band of frequencies.

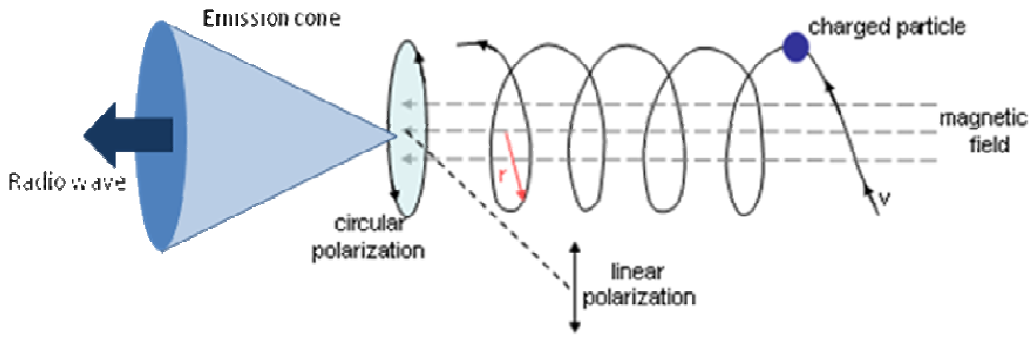


Figure 35. Generation of Synchrotron Emission

It is common for amateur radio astronomers to measure the galactic Hydrogen Line signal, but less so to measure the broad band galactic synchrotron radiation around 1.4GHz, which is much weaker.

The measurement described here shows that the observed signal intensity is getting close to the minimum detectable signal level for a simple radio telescope with a 3m diameter dish antenna.

Whilst the H Line signal is concentrated around 1420.4MHz, the synchrotron emission is spread over a wide spectrum from HF to microwave frequencies. The spectral intensity of the emission falls with increasing frequency (decreasing wavelength), as shown in figure 24. It can be seen that the signal intensity is approximately 40 times less at 21cm (H Line) than it is at 10m.

If measurements or maps of the distribution of galactic synchrotron signals are to be made, then these should preferably be conducted at VHF for the best signal to noise performance.

As amateur radio astronomers will probably not have large VHF arrays, but may well have UHF equipment configured around 1.42GHz for H line measurements, it will still be interesting to measure the synchrotron background at UHF - even though it is at a low level.

The raw data in figure 36 shows a transit measurement of the synchrotron emission at 1419.5MHz across the Cygnus spiral arm. Later in this article we will directly compare this to the H Line measurement through the same galactic feature.

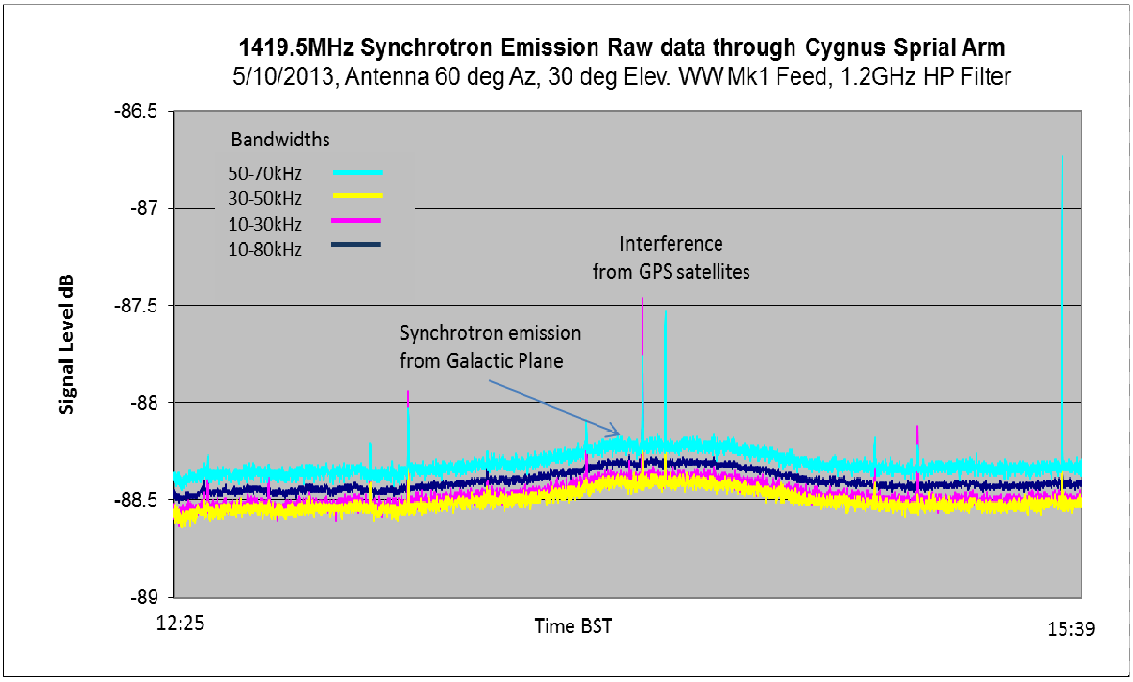


Figure 36. Synchrotron Emission across the Cygnus Spiral Arm

In addition to the “central hump” synchrotron emission feature, there are several examples of interference from GPS satellites as they cross through the antenna beam. Whilst the breakthrough is small (~1dB above system minimum detectable signal), it is bigger than the signal we are trying to measure. Improved filtering (in addition to the 1.2GHz HP filter) in the signal path before the FunCube Dongle Pro+ would help to reduce this interference.

This GPS breakthrough is not seen when using a ‘traditional’ communications receiver such as the ICOM-R7000, which has previously been used to make these synchrotron measurements. This suggests that more rigorous band limiting filters are required in front of the FCD Pro+ for satisfactory performance.

The interference can be automatically removed in this case from the recorded raw data, by using a simple Excel spread sheet formula which compares the signal strength at sample n with the average of preceding samples (n-10 to n-5) and replacing the value for sample n with the value for sample n-10, if the value of the nth sample is greater than 1.05x the average value.

An example of the formula used is:

=IF(G20>(1.05*(AVERAGE(G10:G15))),G10,G20)

The exact selection of parameters in this formula depends on the characteristics of the noise and the interference - and should be tailored for particular situations.

The resulting interference free plot for the 10-80 kHz bandwidth measurement is shown in figure 37.

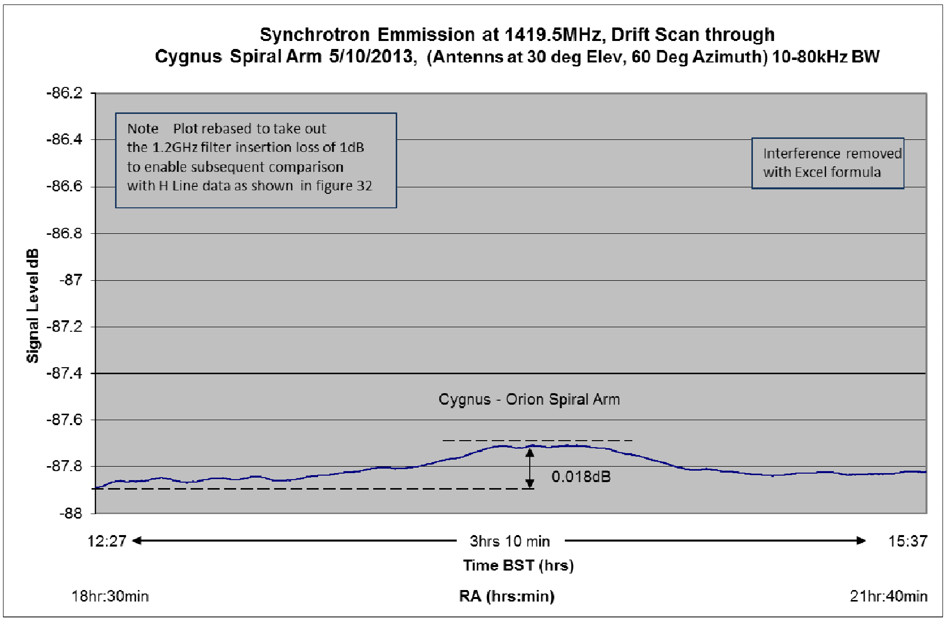


Figure 37. Processed data showing Synchrotron Emission across the Cygnus Spiral Arm

We see that the maximum signal is less than 0.2dB above the system noise. However it has been shown that even this small signal margin is sufficient to enable a map to be made of the synchrotron emission in the galaxy by assembling a number of scans at different declination angles [7]. Figure 38 shows the local galactic arm synchrotron emission on a larger amplitude scale.

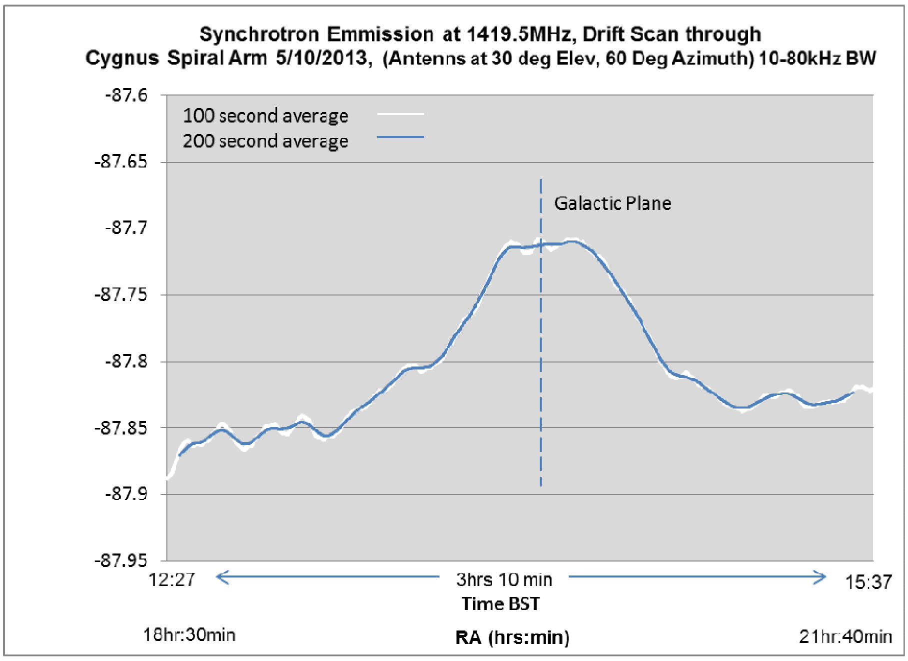


Figure 38. Galactic Synchrotron Emission (expanded amplitude scale)

A comparison of the signal strengths of the Hydrogen line at 1420.4MHz and the nearby Synchrotron signal on 1419.5MHz, is given in figure 39. This shows how relatively easy it is to detect the H line.

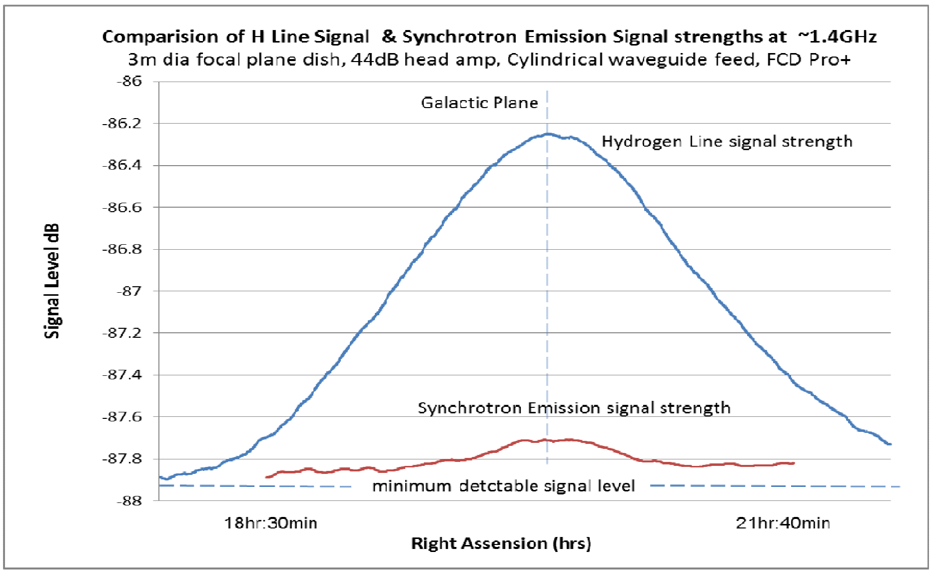


Figure 39. Comparison of H Line and Synchrotron Signal Strengths at ~ 1.4GHz

Finally we show the relationship between the synchrotron signal and the ground noise in figure 40. This is achieved by driving the antenna elevation down from 65^0 to 5^0 and recording the signal amplitude.

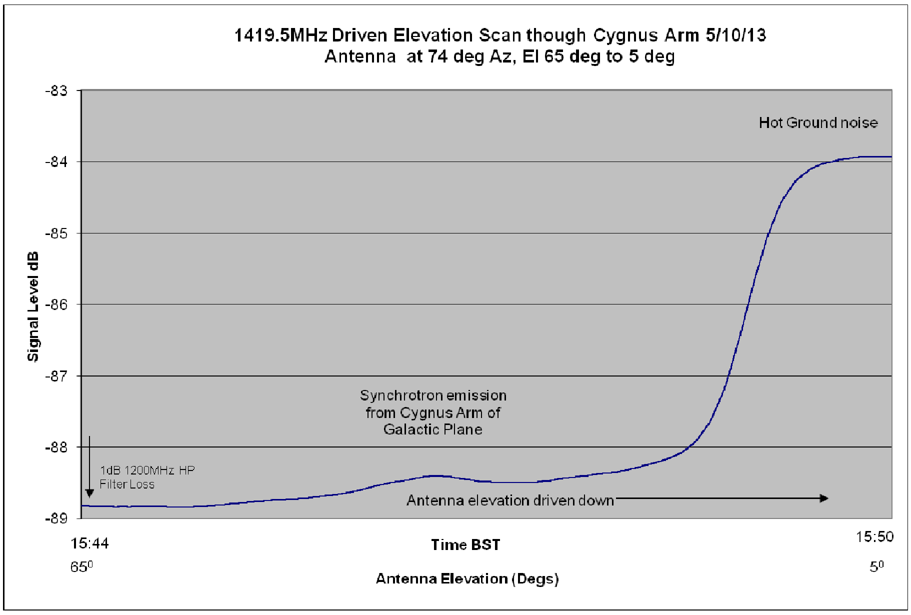


Figure 40. Synchrotron signal and 'Hot Ground Noise'

This plot reinforces the need for low sidelobes and spillover, as even slight leakage into the antenna will compromise measurements of low level synchrotron emissions. Measurements are best made when the antenna can be operated at high elevations to observe the astronomical feature of interest.

Best results are probably obtained with antenna elevations above 40^0 to reduce ground noise leakage to a minimum.

6 Conclusions

1 Several conclusions may be drawn from this exercise in setting to work and 'calibrating' a small 3m diameter focal plane dish radio telescope using the FunCube Pro+ software defined radio receiver.

2 A useful, stable amateur radio telescope operating at 1.4GHz can be constructed using a modest 3m focal plane dish antenna with a 44dB gain 0.3dB noise figure head amplifier and a FunCube Dongle Software defined radio receiver.

3 Spectrum Lab software can be configured to replace the SpectraVue software used in an earlier demonstration of this SDR radio telescope and provides some interference and instrumental noise immunity advantages

4 The main filter in Spectrum Lab can be used to eliminate the 'Zero Spike' noise and the upper band edge noise at 96 kHz produced by the FCDPro+, from appearing as an unwanted component in the measurement records.

5 The 'Watch List' function in Spectrum Lab can be used to divide the full FCD bandwidth into a number of narrower band 'detection records', offering some immunity to narrow band interference that arise during measurements. This option produces 4 signal outputs that can separately plotted.

6 The FCDPro+ may have a setting time before it becomes stable. It is advised that the device is allowed to stabilise for 1 hour before being used to make measurements.

7 Following the stabilisation period, the gain / noise drift is shown to excellent, better than 0.02dB over a 3 hour period.

8 The ratio of the antenna / head amplifier noise to the FCDPro+ noise level was measured to be 11.7dB. This ensures that the measurement performance is dominated by the 'front end' components of the telescope system.

9 The ratio of ground noise (antenna pointing to the horizon) to the cold sky noise level was measured to be 4.1 dB.

10 The incorporation of a coaxial 1.2GHz high pass filter before the input to the FCD Pro+ to reduce the prospect of low frequency signal overloading, resulted in a 1 dB signal path loss. This still maintained a good ratio of 10.7dB above the FCDPro+ noise level.

11 The signal level from a quiet Sun at 1.4GHz was measured to be 11dB above ‘cold sky’ noise level. This equates to 6.1dB above the signal level from the ‘hot ground’.

12 The signal level from the Cygnus Arm of the Milky Way measured at 1420.4MHz (Hydrogen Line rest frequency) was 1.55dB above the cold sky noise level. The ‘clarity’ of this signal was very good, with the 100 point running mean noise level being only 0.02dB. There was no significant ‘noise’ visible on this signal from the Galaxy.

13 A fast motorised elevation scan (~1^0 / second) across the Cygnus spiral arm resulted in no loss of peak signal compared with the longer drift scan measurement.

14 The Cygnus spiral arm synchrotron emission signal is much weaker (1.4dB) than the Hydrogen line signal. It is barely above the system minimum detectable signal at 1.4GHz.

15 Measuring weak synchrotron features requires the ground leakage noise to be kept to an absolute minimum by operating the antenna at high elevations above 40^0.

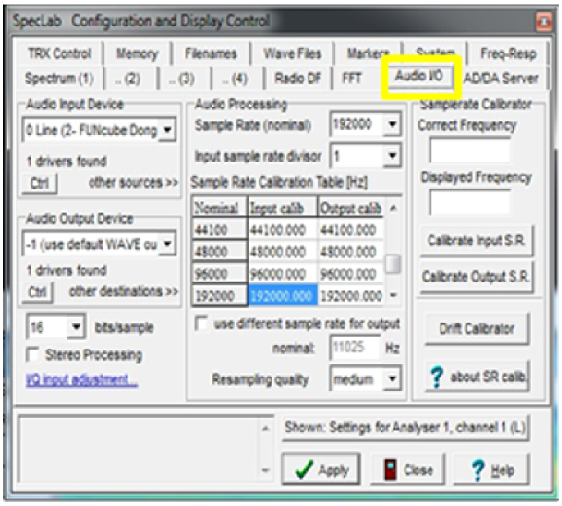
16 This paper has demonstrated the typical key performance parameters that may be obtained from a simple 3m SDR radio telescope and should assist any amateur radio astronomers in setting to work a similar system.

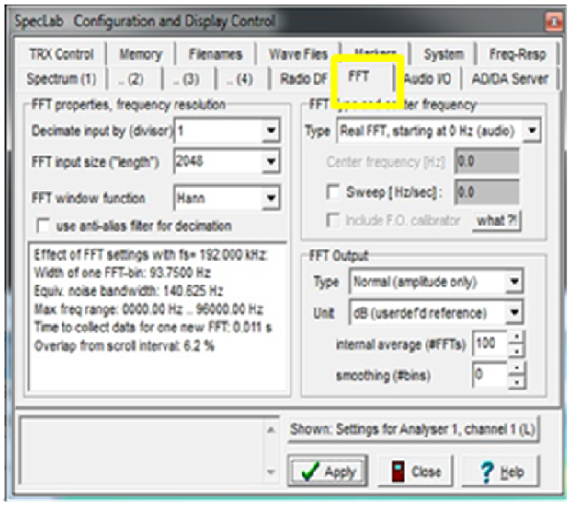
7 Appendix A Spectrum Lab & Hardware Configuration

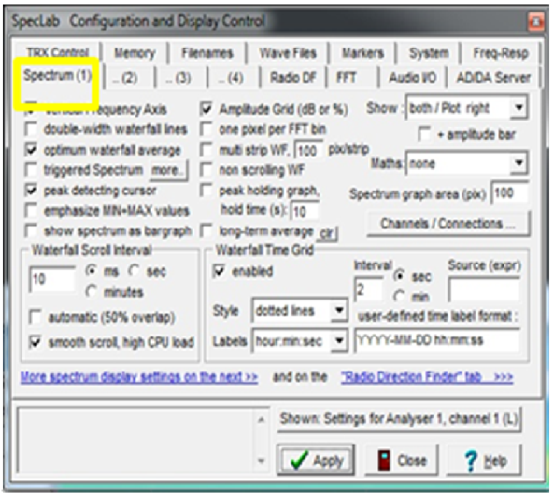
Spectrum Lab Configuration

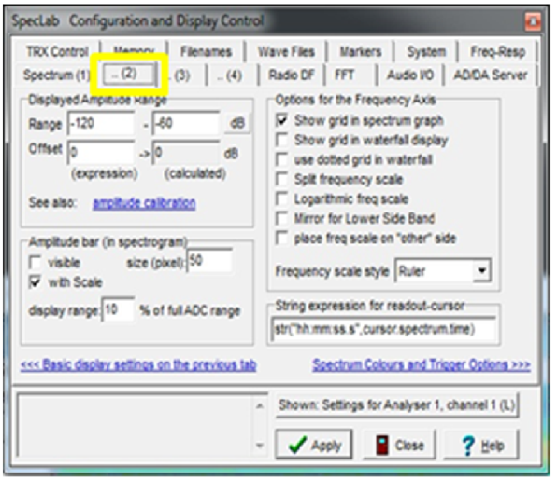
This information is provided to assist anyone wishing to replicate the measurements made in this article. The necessary screens are shown with appropriate settings.

7.1 Basic set up screens:

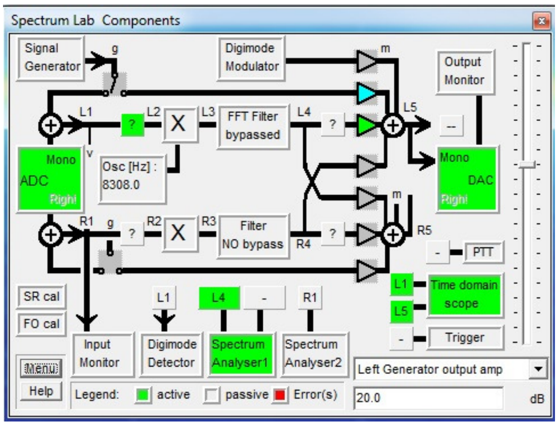


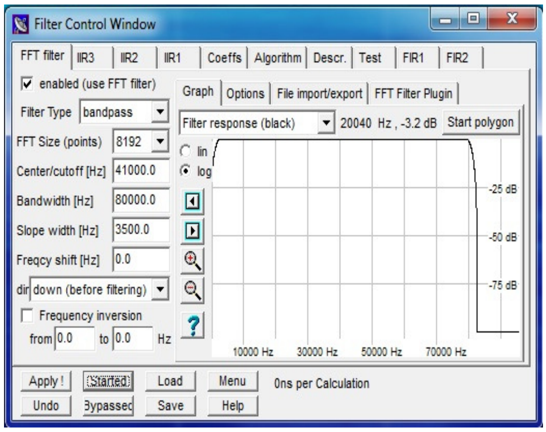




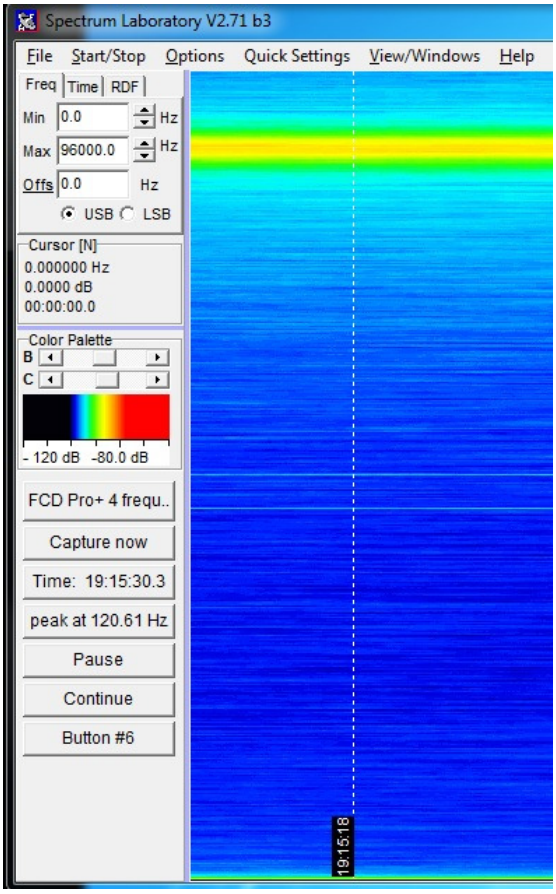


7.2 Component Definition & Filter Control Window:

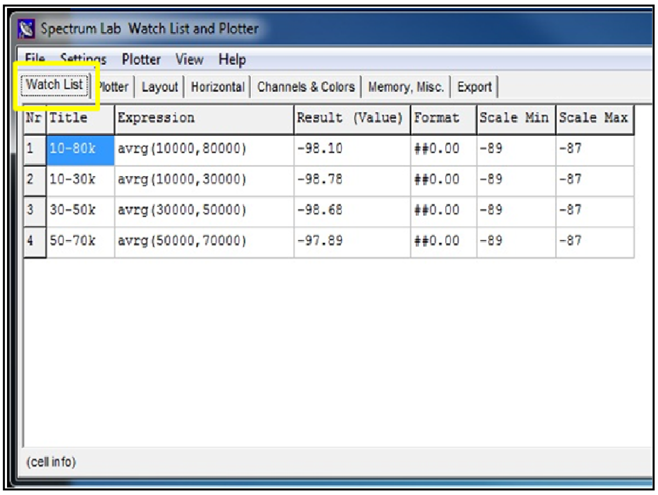


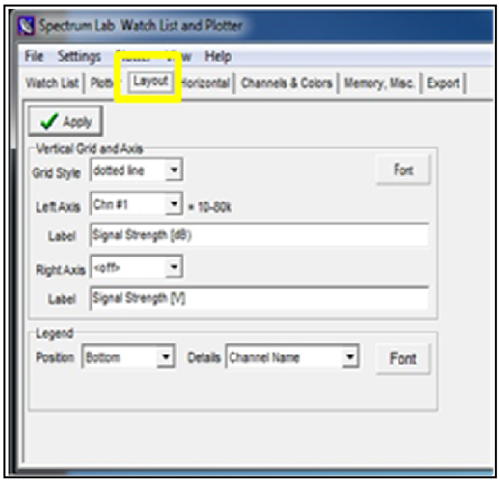


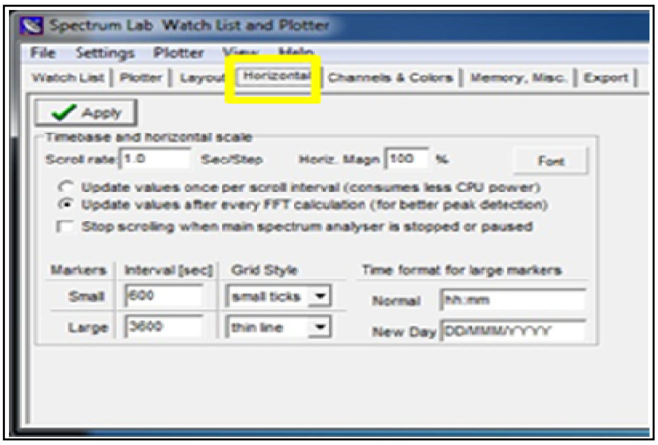
7.3 Main Screen Configuration:

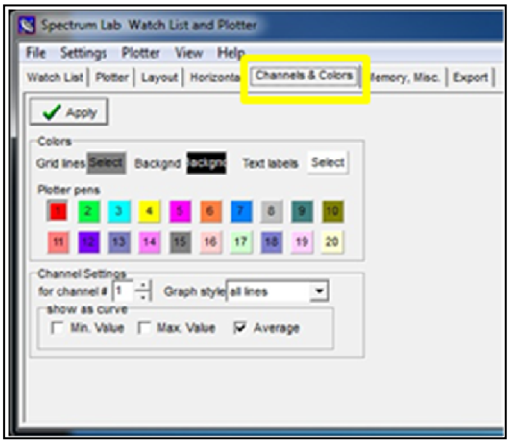


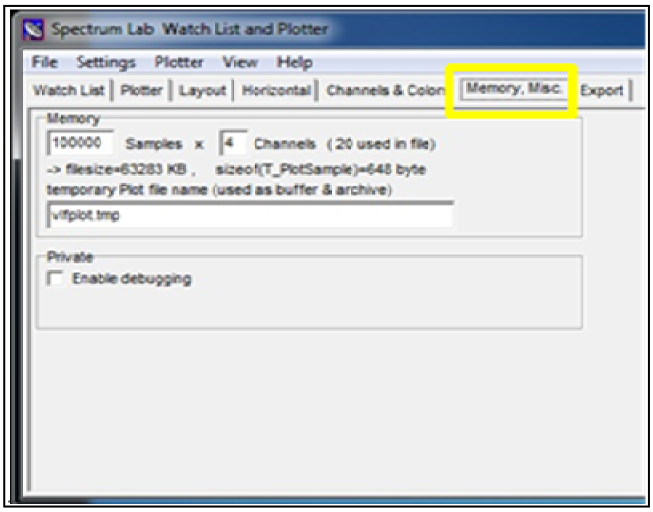
7.4 Watch List Configuration:











7.5 Hardware used in these tests:

Stable broadband
Noise Source

HP Attenuator

FunCube Dongle Pro+

1200MHz High Pass Filter

8 References

1 www.dmradas.co.uk (Downloads - Construction of a 3 metre Amateur Radio Astronomy Dish Antenna for 1420MHz

2 www.funcubedongle.com/ + (groups.yahoo.com/group/FUNcube/)

3 www.britasro.org/radio (downloads - An SDR Radio Telescope)

4 www.moetronix.com/spectravue.htm

5 www.qsl.net/dl4yhf

6 www.radiosky.com/

7 www.dmradas.co.uk (Observations / 1453.5MHz map)