The Commissioning of an Experimental Radio Station at the Royal Observatory

Sean M. Johnston

Supervisor - José Sabater Montes

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Abstract

The upcoming Square Kilometer Array (SKA) represents a large step forward for data-intensive research methods within radio astronomy. This approach will require innovative data workflows and management techniques along with new infrastructures, and is set to become an integral part of research in the future with the advent of new technologies which make it feasible. To perform some low level investigations of data-intensive methods within radio astronomy, and as a potential educational aid for future use, a small scale experimental radio station was set up at the Royal Observatory and two mini experiments conducted.

1 Introduction

Data-intensive science is an emerging research approach which has been described by some as a new fourth paradigm within scientific research, following closely those of experimentation, theory and computer simulation [1]. While this approach, characterised by large-scale data gathering and centred on data-driven exploration-based research, opens doors to many new research possibilities, it also brings with it a whole new series of challenges to be overcome.

The sheer amounts of data produced via this approach requires the development of new innovative ways of managing that data. New analysis techniques are also required to interpret the data and to draw accurate, meaningful results from it.

For example, the upcoming Square Kilometer Array (SKA), which will be the world's largest radio telescope when completed, is expected to have a data transmission rate up to many petabits per second [2]. Supercomputers capable of in excess of 100 petaflops [3] (floating point operations per second) are being designed to handle these vast amounts of data and the calculations that will be required.

It is clear that understanding data-intensive science within astronomy will become increasingly important in coming years as our technological capabilities increase even more and allow these methods to be fully harnessed.

To investigate the basics of these new data-intensive techniques, funding was secured for hardware to build a small scale radio station at the Royal Observatory, based upon Software Defined Radio (SDR) components.

The principle of SDR is the transfer of as many of the functionalities of radio communications from hardware components to programmable software devices as possible, a trend that has mainly been facilitated by the increased processing power and capabilities of software that has been seen in recent years [4]. In general, most SDR systems aim to replace traditional hardware processes, such as the analog-to-digital converter (ADC), digital-to-analog converter (DAC) and modulation schemes, with software-based counterparts [5].

Our station was built with accessibility and education in mind, as affordably and simply as possible. This was to allow our efforts to be reproduced by anyone without too much difficulty or technical experience and to make it more useful as a learning tool, where the focus would be on the process and the data workflow rather than on a complicated setup or pieces of equipment.

We decided to focus our attention on two separate experiments to undertake which would provide different interpretations of the gathered data. The first was detecting meteors via radio scatter which involved analysing the data in search of particular localised events, while the second was tracking the HI neutral hydrogen emission of the Milky Way. A full presentation of these experiments can be found in sections 2 and 3, respectively.

2 Meteor Radio Scatter

2.1 Theory

Throughout the year, Earth passes through various streams of small dust particles which become meteors when they enter the upper atmosphere. Their high velocity produces sufficient heat through friction with air molecules causing them to be vapourised and leaving behind an ionising column of air. These columns can last for up to a few seconds and can be dense enough to reflect radio waves, so provide an opportunity to use radio waves to detect the parent meteor. The optimum frequency range to use for detection lies within the very high frequency (VHF) band at around 40-100 MHz [6, 7].

The scatter of radio waves from meteor trails is completely specular [6], meaning the meteor trails behave exactly like mirrors and all the conventional rules apply. For example, the angle of the reflected wave will be equal to that of the incoming wave. This is especially useful for 'forward scattering' where meteor trails can be used to briefly extend the range of ground-based radio communications for anywhere up to 2000 km [7]. This is the scattering case that will be focused on for this experiment. A diagram of this is shown in Fig. 1.

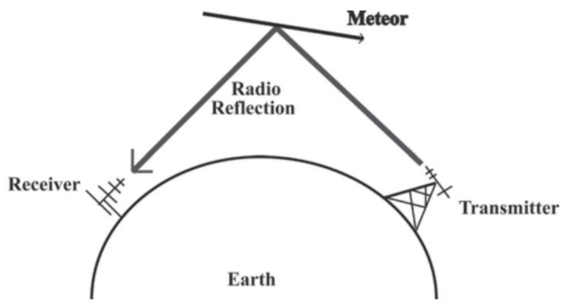

Figure 1: Forward scattering of radio waves from a meteor trail. *J. Lashley*, 2010.

There are two distinct models for meteor radio scatter, dealing with both underdense and overdense trails, respectively. Underdense trails have low scattering electron density and are typically smaller and of lower energy [6]. Here, the trail electron density is low enough to allow the incident waves to penetrate into it and scatter off of individual electrons [7]. On the other hand, overdense trails are characterised by high electron densities, with the central core of the trail appearing more like a plasma [6]. This case is much more difficult to model but can be loosely approximated to the incident waves reflecting from the surface of the plasma-like trail [7].

The process of detecting meteor scatter events should provide an interesting look at how to manage data. Leaving the equipment running for extended periods of time would result in large data-sets where the events of interest are relatively tiny. Devising ways of dealing with this problem and extracting the relevant information is a worthwhile endeavour and should be informative, irrespective of the small scale of our setup.

2.2 Methods

The basis of the setup for this experiment was a pair of SDR receivers: a cheap, single channel NooElec NESDR SMArt Realtek RTL-SDR dongle with up to a 2.4 MHz bandwidth and a more sophisticated SDRPlay RSP2 pro with three antenna channels and up to a 10 MHz bandwidth. Both of these had a USB connector to link up to a computer. The antenna used was a directional Yagi antenna (Yagi-Uda Array), the classic example of which is the UHF (ultra high frequency) television aerial. This type of antenna has a high forward gain which leads to its directionality

[8, 9]. Other requirements included some coaxial cable with reasonably low losses, all of which had a 50 Ω impedance, and an antenna mast which was set up on the observatory roof when in use. Pictures of the equipment can be seen in Figs. 2 & 3.

(a) NooElec NESDR SMArt Realtek RTL-SDR dongle.

(b) SDRPlay RSP2 pro receiver.

Figure 2: The SDR receivers used.

Figure 3: Yagi antenna on the observatory rooftop.

On the software side, the initial plan consisted of using an open-source library called SoapySDR [10] to control the receivers. The main advantage of SoapySDR was that it came with Python bindings to pass control of the receivers on to custom written Python scripts. Installation of this library, however, proved difficult in the beginning and an account of our exploits on this issue can be found in Section 2.3. It will suffice to mention here that installation of SoapySDR was met with eventual success.

Once SoapySDR was installed, two other helper packages were installed that made use of SoapySDR easier: simplesoapy [11], a pythonic wrapper for the SoapySDR library that simplified its usage into a set of basic, understandable commands, and soapy_power [12], a terminal command to run SoapySDR and output a power spectrum. This provided two separate ways of obtaining data.

Due to our inability to transmit our own signals to detect meteors with, the FM frequency band of 87-108 MHz was used due to the large number of commercial radio station transmitters within this band that exist across mainland Europe. Another advantage of using this band is that documentation exists for a large number of these transmitters, freely available on websites such as FMSCAN [13] and FMLIST [14]. These sources of signal are also freely accessible to anyone who wishes to use them.

Before the attempted detection of meteors could commence, suitable directions and low noise parts of the FM band had to be identified. The main disadvantage of using the FM band is encountered at this stage: there is an over-abundance of local commercial radio stations producing noise that makes it hard to detect the brief faint signals scattered off the meteor trails from those distant stations on mainland Europe.

This necessitated the production of a local radio map, showing how the FM band frequency power spectrum changed with direction. This would help identify areas of the spectrum with comparatively low noise in any given direction and therefore which commercial transmitters it would be suitable to detect from.

A Python script was written using the simplesoapy wrapper that would scan a given frequency range in a number of 'hops', whose size was determined by the bandwidth/sampling rate used. This was used to scan the FM band in sixteen directions using the SDRPlay receiver and eight directions using the Realtek RTL-SDR dongle. The Realtek dongle gave better results at this stage as the SDRPlay receiver appeared to have saturation issues in some parts of the spectra and so ultimately the map was produced with the power spectra from the Realtek dongle. We would later discover the source of the saturation issues was in how the automatic gain of the SDRPlay receiver was being set. Once the gain was explicitly set by us, more reasonable results were produced.

The map itself was produced by reading the directional spectra from the Realtek dongle into a second Python script. This took the spectra from those eight directions and interpolated them onto 360 directions, producing a smooth map, which can be seen in Fig. 4.

Once the map was produced, a meteor detection test was performed using the SDR software package 'CubicSDR' [15], which allowed the data from the receiver to be viewed in real-time. Using information about current peak meteor streams and suitable directions to point the antenna from *J. Lashley*, 2010 and information from our radio map, a suitable commercial radio station in Denmark was selected.

Using CubicSDR, any signal at the target frequency above the mean background was set to be played through the audio output of the laptop. This, coupled with the visual signal display on the laptop screen, allowed for easy monitoring of any events. After around 20 minutes, an event with convincing meteoric hallmarks was recorded (See Fig. 5), confirming the functionality of the setup.

Following this success, a further data-set was taken using the soapy_power terminal command with 0.1s integrations and a 1 MHz bandwidth. Another Python script was written to scan this data for possible events above a given significance level.

We had to end this experiment here as time dictated that we move on to the second of the two.

2.3 Results & Discussion

The local radio map produced is shown below in Fig. 4. The colour scale is arbitrary with redder areas representing a stronger signal.

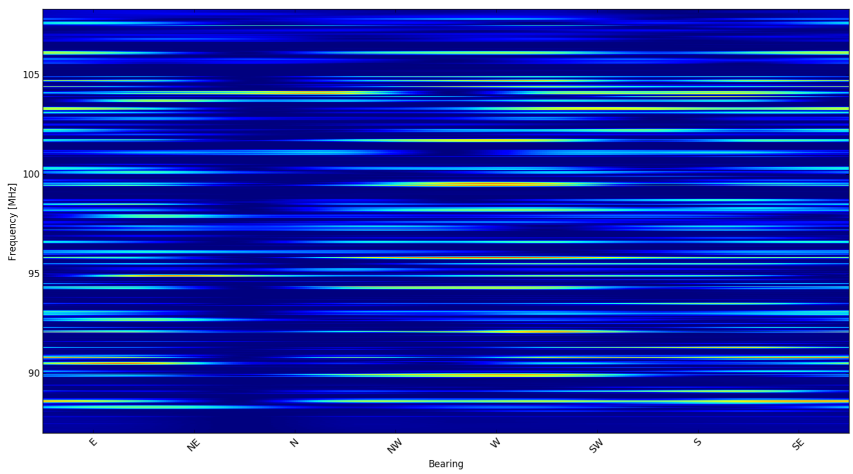

Figure 4: Graphical representation of the produced radio map of signal power against frequency and direction. Redder colours indicate stronger signal.

An interesting feature to note is the low-signal gap across most frequencies between North-East and North. This corresponds to the direction of Arthur's Seat, a large hill within the City of Edinburgh. Whether or not this is the cause of the relative lack of signal coming from that direction is unknown, but it is an interesting point of thought nonetheless.

A screenshot of the initial meteor detection via CubicSDR is shown below in Fig. 5. This was from a commercial radio station near Copenhagen in Denmark, broadcasting at 87.9 MHz. The distance to the station transmitter was around ~800 km and the antenna was pointed towards a bearing of ~072°.

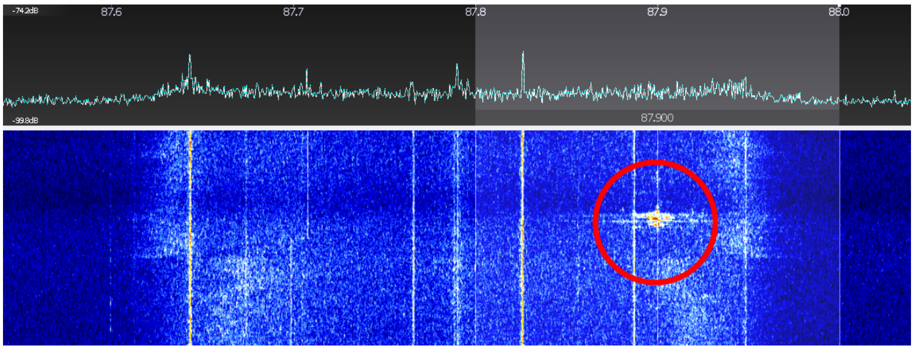

Figure 5: The first meteor detection, from CubicSDR. The vertical axis is time, horizontal axis is frequency in MHz and again, redder colours indicate stronger signal. The meteor signal is highlighted with a red circle.

The signal was as expected for one from meteor scatter; it did not last long, only around a second or so, but, while there, had the appearance of a commercial radio station. The brief second of audio that corresponded to this signal sounded like it contained a voice. Whether that is merely wishful thinking on the part of the author or not is also unknown, but it must remain in the field of speculation as no recording of the audio signal was able to be made. It did lend an excitable credence to the event in our minds at the time.

The results from the initial data-set taken after the above detection are shown in Figs. 6 & 7. Initially, the data-set was qualitatively analysed manually by plotting a heatmap and identifying by eye the strongest event. This is what is shown in Fig. 6.

A more thorough and quantitative analysis method was required as the manual 'by eye' method was not practical for larger data-sets. There was also nothing to be learned that way about the handling of large data-sets.

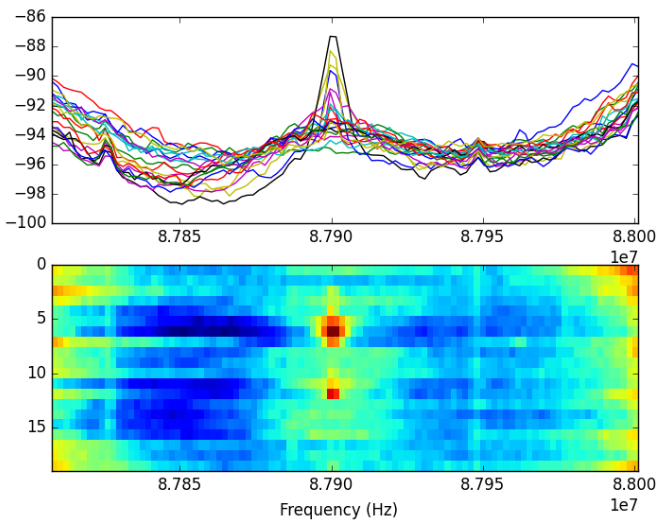

Figure 6: A heatmap and spectral plot of the 20 integrations around the main meteor event within the data-set. The vertical axis of the upper pot is Power in dB, while on the lower plot can be thought of as the time axis. Again, redder colours indicate stronger signal.

After much thought and an unsuccessful trial of detecting changes from one integration to the next, the following method was devised: each integration's spectrum was compared against the median spectrum, and its standard deviation, of a specified number of previous integration spectra. For example, the event detected in Fig. 7 compared each integration spectrum against the median spectrum of the previous 50 integrations. The detected event deviates from that median by 6.3 standard deviations, which is a fairly high confidence level. It also matches the event detected by eye earlier.

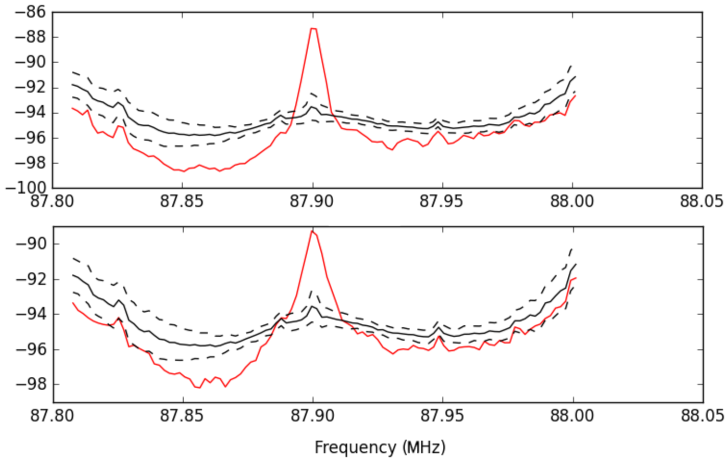

Figure 7: The results of applying the event detection script to the data-set. The red lines are the event spectra, while the black lines are the medians and standard deviation envelopes of the previous 50 integrations. These events were detected at a 6.3 standard deviations significance level. Again, the vertical axes are Power in dB.

There are some improvements that could be made to this experiment. Ideally, more data should have been taken to test and improve our data handling scripts. A more sophisticated script was written that combined the data collection and event detection parts of the data workflow into one unit, such that it would keep gathering data but only saving regions where an event was detected. This would maintain the amounts of stored data at manageable levels and is one way of dealing with large data acquisition. However, this method is only as good as the algorithm that decides which data to keep and which to throw away, so should have been looked into more thoroughly and had proper testing. Much of our working time, however, was postponed by inclement weather conditions which was a significant contributor to the low amounts of testing we were able to carry out.

Another significant time sink of this experiment was getting the software working properly. It was important that the flexibility of using Python to run everything was something that we had access to. In that regard, SoapySDR was the best library to use, even if it presented a number of challenges at the beginning.

Aside from the Python compatibility available with SoapySDR there were other advantages with using this library. SoapySDR was open-source and freely available online, which conformed to our aims of having our methods be as accessible as possible. SoapySDR was also advertised as being vendor neutral and platform independent [10]; it was almost completely general, allowing it to interface with most SDR devices and environments.

However, as previously mentioned, there were some initial difficulties to overcome. The library would fail to build or compile successfully on the laptop, rendering our first attempts utterly non-functional. Not knowing where the issue was in the build or what was causing it to fail, we decided to try other software libraries instead.

First, we tried the 'rx_tools' library [16] which used the SoapySDR SDR support library within it and provided commands for the terminal. This installed successfully and ran the Realtek RTL-SDR dongle but there were issues with the power spectrum output from the SDRPlay receiver, suggesting problems somewhere in how this library interfaced with it.

We then tried two separate libraries: librtlsdr [17, 18], which did not have support for the SDRPlay-type receivers, and SDRPlayPorts [19], an experimental port of the librtlsdr library for

SDRPlay receivers. Again, there were issues with how these libraries were computing the power spectra of the data from the receivers. We decided instead to output the data in raw I/Q signed binary format directly from the receivers and experiment with handling the data and analysing it ourselves. This was met with some success but was not a practical approach in the long-run; file sizes were too large to handle (100 MB for 10s, with a 2.4 MHz sampling rate), which was contradictory to our aims of keeping data at a manageable size.

It was at this point that a second attempt at installing the SoapySDR library was successful, allowing the experiment to proceed more smoothly. That was not the end of the software issues as the interface with the hardware remained tenuous throughout the rest of the experiment; it was the source of a lot of the main problems we faced. While the SDRPlay receiver was more sophisticated, powerful and expensive than the cheap Realtek dongle, its performance was very inconsistent. The Realtek dongle just worked for the most part, suggesting that the underlying cause may have been to do with the SDRPlay drivers within SoapySDR.

All of this being said, the groundwork is now in place for future work to be carried out. The initial startup issues have mostly been rectified meaning that future work would be primarily dealing with the main aims of the experiment and less time would be consumed by troubleshooting.

2.4 Conclusion

An experiment was undertaken to detect meteors from radio scatter as a means to investigate data-intensive handling techniques. While some meaningful data workflows were produced and positive results achieved, the aims were not fulfilled in their entirety. We suffered some challenging problems surrounding the installation and usage of the required software and the interfacing of that software with the hardware. These problems were quite time consuming and so we were not able to apply and test the data handling methods as fully as we would have liked. However, there is now a strong basis to move forwards from, at a later point.

3 Milky Way HI Emission

3.1 Theory

Throughout the universe is distributed gas clouds of neutral atomic hydrogen which forms a large part of the composition of our Milky Way galaxy. Using radio observations, the distribution of atomic hydrogen in the Milky Way can be mapped [20], such as the recent full sky survey by the HI4PI Collaboration in 2016 [21].

Neutral atomic hydrogen has a distinctive marker: a unique 21 cm emission line corresponding to a hyperfine splitting of its ground state [22]. This is to do with the relative spin orientations of the atom's component proton and electron whereby, if the spins are parallel, the state has a higher energy than if the spins were anti-parallel [23].

This 21 cm emission is detected from all directions meaning that neutral hydrogen gas is distributed throughout the Milky Way and maps of this emission show much of the galactic disk is filled with this gas [20]. Therefore, directions looking within the galactic plane will have a higher detected emission than directions looking out of the plane as there is more gas in the line of sight.

As Earth rotates through one day, different parts of the Milky Way will be in the sky. By leaving a detector pointing in a fixed direction relative to Earth, its line of sight will trace out a pathway across the sky because of this motion. This creates a simple way to measure the direction-dependent variation in the strength of the Milky Way 21 cm emission.

Tracking the changes in the Milky Way 21 cm emission will also provide another avenue to investigate methods of data handling but in a different way to the previous experiment. Before, the relevant data were small localised events within the larger data-sets that had to be detected by some algorithm. In this experiment, all the data is relevant as it is a constant measurement that is being made.

3.2 Methods

The 21 cm line corresponds to a frequency of 1420 MHz, which required an antenna suitable for ultra high (UHF) frequencies. The biquad antenna was chosen as it was simple to build, easy to use, was fairly compact and offered good directionality and gain. A schematic can be seen in Fig. 8

and pictures of the two antennas built from it can be seen in Figs. 10a & 10b. This final point was important due to the relative weakness of the 21 cm emission. It is a comparatively recent antenna design consisting of two diagonal square loops of wire arranged in a 'bow tie' shape mounted on a reflector plate. It can be thought of as two corner-driven square-loop antennas grounded and excited at the same point [24].

Two biquad antennas were built to the specifications [25] detailed in Fig 8 and Table 1, with optional side reflectors included. The sides of the two squares on the element had to be a quarter of the target wavelength and the separation between the back reflector plate and the element had to be one eighth of the target wavelength, for optimum results [24, 25]. If the element was not built to the correct size, it would not be tuned properly to the 21 cm line.

The first was built from a copper-clad fiberglass PCB material with the side reflectors cut separately and soldered onto the back plate. The second was built from plastic-coated copper sheet with the side reflectors bent to shape. Both antenna elements were built from plastic-coated copper wire which was also simply bent to shape.

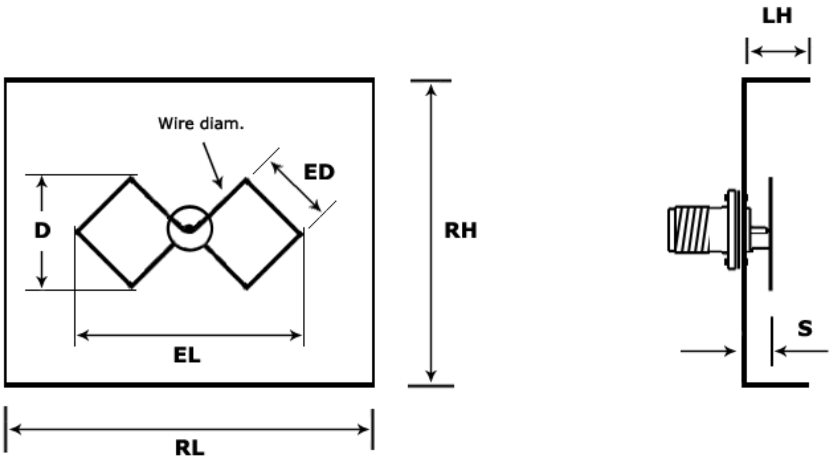

Figure 8: Schematic of the biquad antenna used during construction. The corresponding values to the labelled measurements can be seen in Table 1. *M. Skaringa*, 2014.

Table 1: Measurement values of a biquad for 1420 MHz from *M. Skaringa*, 2014. These values correspond to the labelled measurements in Fig. 8.

Measurement	**Value, *cm***	**Measurement**	**Value, *cm****
ED	5.28	S	1.8
D	7.5	LH	5.0
EL	14.9	Wire Length	50.0
RL	21.3	Wire Diameter	2.11 mm
RH	21.3	Wire Area	3.5 mm^2

*unless specified.

Two female N-type coaxial panel mount connectors were attached to the backs of the main reflector panels and provided the connection points for the antenna elements. The centre of the elements were attached to the inner wire of the connector and the ends attached to the outer sheath and, by extension, the back reflector plate. This was also the place where the wire to the receiver would be connected.

Once the antennas were built, they needed to be tested to ensure they were built properly and tuned to the correct frequency. An RF bridge, along with a signal generator and spectrum analyser, was used to do so. Inverted peaks are displayed on the spectrum analyser at the 'natural' frequencies the antennas will radiate at. Through the antenna reciprocity theorem [26], these will also be the frequencies with the highest gains.

As the signal from the 21 cm line is relatively weak, two cheap pre-amplifiers were connected between the antenna and receiver and powered with a low-noise power supply. To increase the received signal even more, the antenna was mounted onto a 1.1 m radio dish as shown in Fig. 9.

Figure 9: Picture of the plastic-coated copper sheet biquad mounted onto the 1.1 m radio dish on the observatory rooftop. The green bucket and guy ropes are to provide stability to the dish.

The rest of the hardware used was the same as before: Realtek RTL-SDR dongle, SDRPlay receiver and laptop. The software used was also the same as before, thus removing some of the headaches associated with its setup.

3.3 Results & Discussion

The building of the first antenna provided a useful learning experience for when it came to build the second. Soldering the panel mount connector to the back of the reflector plate proved difficult. Even though the copper cladding was only very thin, the heat from the soldering iron was still being radiated away fairly quickly, but the use of a hot air blower helped solve this issue. As the second antenna was built from pure copper sheet, this heat-loss would have been more pronounced. As such, a screw-mounted connector was instead used for this antenna.

(a) The first antenna, built from copper-clad fiberglass PCB.

(b) The second antenna, built from plastic-coated copper sheet.

Figure 10: Photographs of the two biquad antennas built.

The results from the antenna tests with the RF bridge were not encouraging, as can be seen in Fig. 11. The inverted peaks were not centred on 1420 MHz as hoped, rather somewhere around 1390 MHz. There also appeared to be other, potentially stronger, inverted peaks to the far right but again not centred on 1420 MHz.

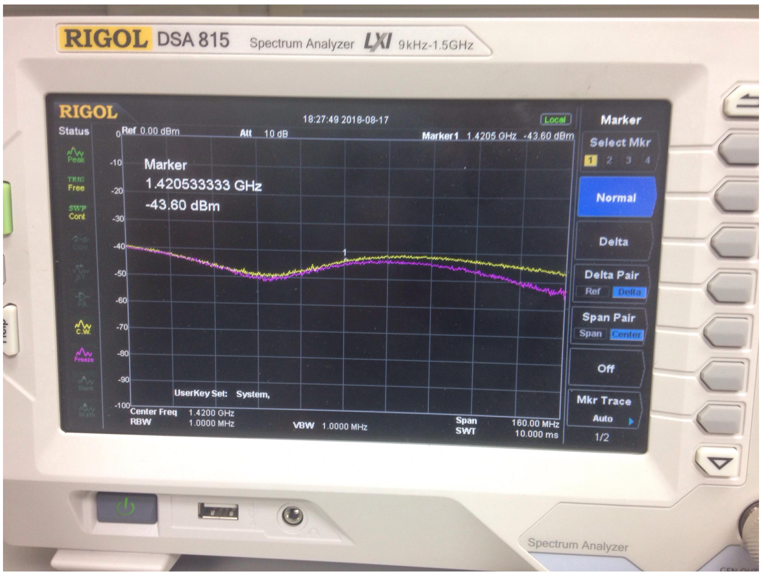

Figure 11: The results of the antenna tests on the spectrum analyser. The yellow and purple lines represent the first and second antennas, respectively. The plot has a 160 MHz span, centred on 1420 Mhz.

The spectra from both antennas appeared very similar suggesting there was a systematic problem with the construction of the antenna elements. They were built by hand, by eye and with only a steel rule to check the measurements and there is a reasonable case for the elements not being accurately built. In future, it may be prudent to accurately construct some sort of jig to make the element with, ensuring its dimensions are correct.

There was also a suspicion that there was an issue with the RF bridge used. It was, along with the pre-amplifiers, bought cheaply online and there may be issues surrounding its quality. A small professionally made Yagi antenna tuned to 850 MHz was also tested to gauge what signal a well-built antenna would produce but the results from that were not as expected, casting more doubt onto the cheap RF bridge used. There are plans to purchase a more expensive RF bridge from a more reputable source to test the antennas with, along with some better pre-amplifiers and RF filters.

The antenna was mounted to the dish and set up on the observatory roof over one night anyway, but nothing meaningful could be extracted from the data recorded. Again, weather played an important role here as the radio dish was quite susceptible to the wind, necessitating the use of a heavy weight and ropes to keep it anchored down (See Fig. 9). It was possible, however, to simulate what sort of result would have been expected from a successful experimental setup. The expected path that would have been traced out by the line of sight of the antenna was simulated using the Python PyEphem module [27, 28]. A full sky survey image of the neutral hydrogen emission was then loaded into Python and the simulated path projected onto the survey image. The pixel intensity values along the path could then be used as a measure of the emission intensity expected. The result of this simulation is shown in Fig. 12. As can be seen, two peaks would be expected each day as the line of sight passes twice through the galactic plane as Earth rotates. One peak is stronger, corresponding to a observation direction towards the galactic centre.

There is much scope for future work on this experiment. The plans to purchase more reputable hardware components such as a new RF bridge, pre-amplifiers and RF filters may provide more promising results. At such a time, there could then be drawn a comparison between the emission simulation and the recorded data to measure the effectiveness of the experimental setup. At this time, however, this experiment has produced no results in regards to the Milky Way neutral hydrogen emission or in larger scale data handling.

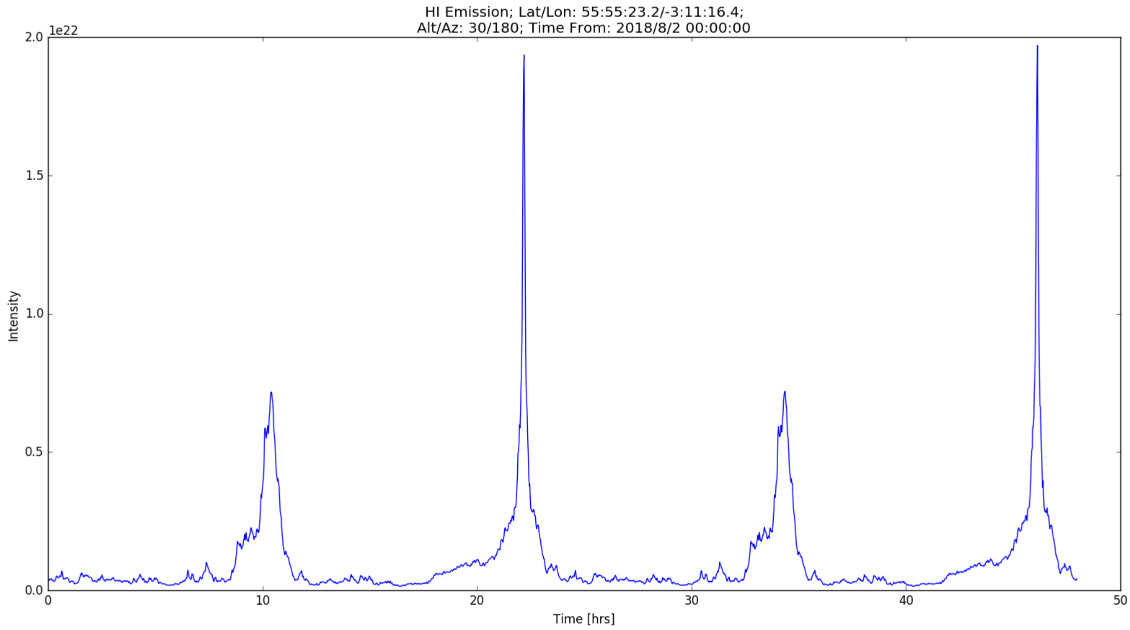

Figure 12: The results of an expected emission simulation with an observer located at the Royal Observatory looking South at an altitude of 30° for two days from midnight on the 2^{nd} August 2018. The vertical axis is an arbitrary relative intensity scale and the horizontal axis is time in hours.

3.4 Conclusion

An experiment to track the 21 cm neutral hydrogen emission was carried out to investigate some more data-intensive research techniques. The experiment, while interesting to undertake, was ultimately not successful. No real data was able to be taken so nothing could be investigated from it. However, there are plans to upgrade some of the hardware components to see if that yields any better results.

It may be that the antennas have not been built properly which could be fixed without too much difficulty by replacing the antenna elements. They play the biggest role in the tuning of the antennas so new ones could simply be remade to a higher accuracy to replace the current ones. There should be no need to rebuild the back or side reflectors.

Such changes, if successful, would then allow the aims of the experiment to be fully achieved and hopefully provide some meaningful insight into the management of large amounts of data. As with the previous experiment, there is a strong basis to move forwards from at a later point.

4 Final Remarks

A small experimental radio station was set up at the Royal Observatory to investigate data-intensive research techniques on a small scale and to provide an educational resource for future use. Two mini experiments were carried out as a basis for this investigation with moderate results.

The first produced some usable data and some data management techniques were able to be applied with promising success, although time constraints limited just how much could be drawn from it. The second did not provide any usable data as the experimental setup did not function as intended.

Many unforeseen challenges were faced and solved, which was a major consumer of the available time. However, as many of those challenges pertained to the initial setup and configuration of the equipment and the software, most of them need not be faced again, leaving open the door for future attempts.

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Personal Statement

I do not regret my decision to undertake a summer project this year as it was both an enjoyable and educational experience. It gave me my first supervisor/student relationship and a preview of the working style on a Seniour Honors project, which will be useful to me very soon. My ability to work independently and with initiative has certainly improved, especially with new material and concepts and in areas I am not familiar with.

I was invited to give a short presentation as part of the project which was quite a daunting prospect for me, but I am glad that I decided to go ahead with it as it served to reassure me in my presentation skills. I have also gained a heavy appreciation for just how unpredictable practical experimentation can be. Facing as many problems and challenges to overcome as we did provided a unique educational experience.

Lay Summary

Some modern radio astronomy techniques produce extremely large amounts of data, presenting new challenges in how that data is managed and analysed. With a grant for some hardware, we set up an experimental radio station to investigate methods of data management and analysis by carrying out two small experiments: detecting meteors from radio signals reflected from them and tracking neutral hydrogen gas emission from our Milky Way galaxy. These experiments were undertaken with the aim that others may be able to reproduce the work that we have done and learn from it as we have.