

Observing Jovian Decametric Radio Emissions with a Software Defined Radio Telescope

David Kirwan, Dr. Alan Davy*, and John Ronan*

Waterford Institute of Technology,
Dept of Computing and Mathematics,
Cork Rd, Waterford City, Ireland
dkirwan@tssg.org
<http://www.wit.ie>

Abstract. The abstract should summarize the contents of the paper and should contain at least 70 and at most 150 words. It should be written using the *abstract* environment.

Keywords: radio astronomy, software defined radio, digital signal processing, gnuradio, hackrf

* Supervisors

Acknowledgements

This dissertation would not have been possible without the support of the following people.

To my supervisors Alan and John for their patience, guidance and sharing of knowledge during this process. Thank you, it has been a real pleasure working together.

To my lecturers at the Waterford Institute of Technology, you have all been so open and free with your sharing of knowledge, it has been an absolute pleasure learning from you.

To my partner Michael, I'm keenly aware standing in the freezing cold at 02:00 helping me put up radio antennas might not have been the most exciting thing you've partaken in all year, but I couldn't have done it without your help. Thanks for your constant encouragement and for putting up with me during this.

To my sister Jean, you inspired me to work as hard as I have these last 6 years. I wanted to make you as proud of me as I am of you. If you beat me to Ph.D, I'll buy you a bag of chips in Roccos.

To my father, I can only imagine the conversations we might have had, I suspect you would have loved playing with this equipment as much as I have.

To my mother, thank you for your friendship. You have always been a positive influence in my life. Some day you must sit down and explain how you can walk past, and in the time it takes to cross a room and without any prior involvement, solve a problem I have been struggling with for days.

To my four dogs Noah, Oscar, Rosie and Dora, you are the best mutts a man could ask for.

Table of Contents

Observing Jovian Decametric Radio Emissions with a Software Defined Radio Telescope	1
<i>D. Kirwan</i>	
Glossary	4
List of Figures	7
List of Tables	8
Introduction	9
Research Hypothesis	15
Methodology	17
Research Questions	20
Literature Review.....	21
Testbed Build and Verification	26
Special Resources Required.....	26
Antenna Build.....	27
Listening Site Suitability	30
Verification of the Radio Receiver	32
Capturing DAM Emissions	36
Research Question 1	38
Determine SDRT Power Requirements	38
Determine SDRT Computational Power Requirements	44
Determine SDRT Network Connectivity Requirements	45
Research Question 2	47
Flag Amateur Radio Enthusiast Transmissions.....	47
Flag Natural Emission Sources.....	50
Research Question 3	52
Capturing DAM Emissions with the RTL2832 DAB SDR	52
Implementing a HackRF Compatible Flow-Graph in GNURadio	56

Conclusions	60
Thesis Appraisal	61
Contribution to Research Knowledge	62
Future Work	63
Appendices	64
Bibliography	70

Glossary

DAM decameter radio emissions in the 10-100m wavelengths. 9, 11–18, 20, 21, 26, 27, 35, 36, 51, 52, 58, 59

DXCluster DXCluster - Number of DXServers connected together into a cluster, where amateur radio enthusiasts can share spotted instances of radio contact between each other. 47

HF High Frequency usually refers to radio frequencies in the 3MHz - 30MHz. 11, 12

IFT Io Flux Tube is a cylindrical area of space containing magnetic field lines. 10, 21

IOT Internet of Things a buzzword for everything connecting to everything. 18, 20, 37

IPT Io Plasma Torus is created by Jovian atmospheric electrons ionizing neutral atmospheric gas such as sulphur in orbit around Io. 9

IQ Imaginary Quadrature signal - Complex signal data and quadrature phase values in a digital signal sample. 20, 34, 51

LOFAR Low Frequency Array - radio interferometer constructed in the north of the Netherlands and across europe <https://www.astron.nl/lofar-telescope/lofar-telescope>. 30

preamp preamplifier - is an electronic amplifier that prepares a small electrical signal for further amplification or processing. 30, 34

RF Radio Frequency is a rate of oscillation which corresponds to the frequency of a radio wave. 29, 34

MW MW - Medium Wave frequencies usually in the wavelengths 300 kHz - 3 MHz. 6, 32, 33

RSGB RSGB - The Radio Society of Great Britain <http://rsgb.org/>. 32

SDR Software Defined Radio is the creation of radio functions within software rather than hardware. 7, 15, 17–20, 23, 26, 29, 34, 51, 55, 58, 60

SWR Standing Wave Ratio is the ratio of the maximum peak voltage anywhere on a line to the minimum value anywhere along a line. 27, 28

List of Figures

1	Decametric Radio Emissions [Ashcraft, 2013]	9
2	Neutral Gasses in Orbit of Io [Belcher, 1987]	10
3	Magnetic Flux Tube linking Jupiter and its satellite Io [Belcher, 1987]	10
4	Alfvén Waves following Io through its orbit and the DAM Emission cones [Bose et al., 2008].....	11
5	Irish Regulatory Transmission Ranges [Comreg, 2014]	12
6	Wavelength Equation	12
7	Wavelength Equation for Real World Half Wavelength Dipole Antenna	13
8	Wavelength Equation for Real World Half Wavelength Wire Antenna .	13
9	Ideal DAM Emissions types from Jupiter [Wilkinson and Kennewell, 1994]	14
10	Dual Dipole Antenna Beam at 20FT and 135deg phasing South [NASA, 2012b]	15
11	Dual Dipole Antenna Array Beam[NASA, 2012b]	16
12	Dual Dipole Antenna Array [NASA, 2012b]	16
13	Radio Jove graph showing Jupiter's max altitude 2014 [Radio-Sky-Publishing, 2014]	19
14	Sampling an Analogue Signal [Smith, 2003b]	22
15	Sampling Theorem aka Nyquist-Shannon sampling theorem [Smith, 2003b]	23
16	I/Q Samples Helix [Kuisma, 2014].....	23
17	I/Q Samples Polar Plot [Kuisma, 2014]	24
18	Measuring the SWR of the antenna with an SWR Analyser	27
19	Standing Wave Ratio Equations	28
20	Calculating P_r for the antenna	28
21	Dual Dipole Antenna Deployment	29
22	Site Survey performed using a Tektronics SA2600 Spectrum Analyser.	30
23	Site Survey performed using HackRF One	31
24	LOFAR Site Suitability Survey performed at Birr Castle [McCauley, 2013]	31
25	Comparing propagation of MW radio signals during day and during night/solar eclipse [Nichols, 2015a]	33
26	Plot of signal power vs time during 20th March 2015 solar eclipse	35
27	DAM Emissions	37
28	DAM Emissions	40

29 Calculating Amps using Watts and Voltage.....	41
30 Average Daily Sunshine in Waterford	42
31 Solar Plots	43
32 DXCluster Client Architecture	47
33 DXCluster data	49
34 Haversine Formula	51
35 Blitzortung data	51
36 24MHz - 28MHz Spectrograms of rtl_power data plotted using heatmap.py	54
37 24MHz - 40MHz Spectrograms of rtl_power data plotted using heatmap.py	55
38 Converting in-phase and quadrature-phase to power values	56
39 Total Power Meter Implemented in GNURadio [Nelson, 2015].....	56
40 Radio Skypipe Software Power Plot [Radio-Sky-Publishing, 2015]	57
41 Graph of calibrated noise temperature [Nelson, 2015]	58
42 Converting Power(V) to Temperature(K)	58
43 GNURadio flow-graphs to generate total power plots from saved data.	59
44 A searchlight beam model of Jupiter's decametric radio emissions [Imai et al., 2008]	64
45 Io Flux Tube and the Plasma Torus [Lang, 2010].....	64
46 21MHz Shortwave Loop Design	65
47 Distance between the Birr and Kilkenny site survey	66
48 Signal Modulation	66
49 Partial Solar Eclipse 20th March 2015 [timeanddate.com, 2015]	67
50 SDRT Dual Dipole Antenna Design based on NASA RadioJove	67

List of Tables

1	Most common types of DAM Emissions from Jupiter [Wilkinson and Kennewell, 1994]	14
2	Literature Review Synthesis Matrix	25
3	Antenna Build Cost	29
4	Average Noise Measurements at Kilkenny Listening Site compared to Birr Listening Site [McCauley, 2013]	32
5	System Power Requirements	43
6	System CPU Power Requirements	44
7	Networking technologies transferring 2GB data	45
8	Sample DXSpider Data Packet	48
9	Sample Blitzortung Data Packet	50
10	RTL vs HackRF and SDRT Requirements	53

Introduction

It was discovered in 1954 by Burke and Franklin [1955] that the planet Jupiter emits radio transmissions in the decameter (DAM) range (*10-100 m wavelengths*), and the inner Jovian satellite Io appeared to have a strong control effect on these emissions [Belcher, 1987]. Jupiter's radio emissions range between 4 MHz to 40 MHz while emitting most strongly at 8 MHz [Wilkinson and Kennewell, 1994]. Due to interference from human short wave radio sources between 4-15 MHz coupled with the attenuation of these signals below 8 MHz or the refraction off Earth's ionosphere, the majority of emissions have been observed up in the 15-25 MHz range where this interference is less [Wilkinson and Kennewell, 1994]. The emission signal strength quickly diminishes above this range for ground based listening sites [Wilkinson and Kennewell, 1994].

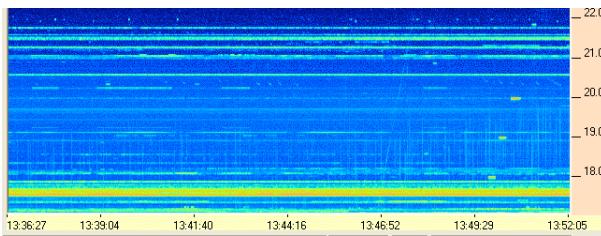


Fig. 1: Decametric Radio Emissions [Ashcraft, 2013]

Data collected by the two Voyager spacecraft in 1979 [Belcher, 1987] and the later Galileo mission in 1995 [Kivelson et al., 1996] added hugely to the understanding of the plasma interactions between Jupiter and Io and the source of the DAM emissions. It was discovered that the Io has a thin atmosphere made up of a number of neutral gasses namely sodium, potassium, sulphur, and oxygen as shown in Figure. 2. It is generally thought these gasses have been emitted through volcanic activity on the surface of the moon [Belcher, 1987]. The gasses in orbit of Io have a very short life time, due to collisions with magnetospheric electrons. This gives rise to a plasma torus (IPT) which co-rotates with Jupiter itself [Belcher, 1987]. This can also be seen in Figure. 2 which shows the IPT.

The local co-rotation speed of the plasma torus is faster than the Keplerian orbit of the moon, and the plasma overtakes Io in its orbit at 57 km/s^{-1} [Belcher,



Fig. 2: Neutral Gasses in Orbit of Io [Belcher, 1987]

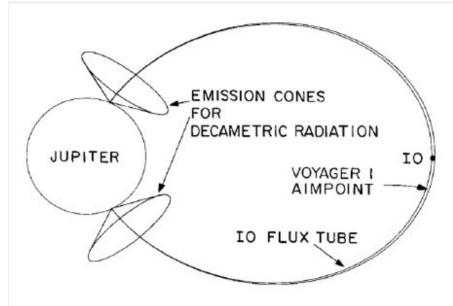


Fig. 3: Magnetic Flux Tube linking Jupiter and its satellite Io [Belcher, 1987]

1987]. Figures 3 and 45 detail diagrams of the Io Flux Tube (IFT) which is a cylinder shaped tube of space containing Jovian magnetic field lines [Belcher, 1987] which link Io to Jupiter's ionosphere at both poles. A large portion of the decametric emissions come from the area where this IFT meets the Jovian ionosphere [Belcher, 1987].

Io acts as a unipolar conductor as it orbits within this flux torus [Bose et al., 2008]. Alfvén waves are regularly produced which carry an electric charge along the magnetic field lines between Io and Jupiter [Bose et al., 2008] thereby acting as a standing wave [Bose et al., 2008]. These Alfvén waves reflect between Jupiter's ionosphere at poles and Io up to 9 times [Bose et al., 2008] before dissipating as they follow Io through its orbit.

It appears the source of the DAM emissions are largely due to these reflections of the Alfvén waves off Jupiter's ionosphere in both the northern and southern regions [Bose et al., 2008]. See Figure. 4 which shows the Alfvén wings reflecting from Jupiter's Ionosphere creating emission cones.

The DAM emissions radiate outwards in the shape of a cone as show in Figure. 3 [Belcher, 1987]. When Io is at specific points in its orbit of Jupiter, these emission cones are pointing in the direction of Earth, at which point emissions can be picked up at ground based radio telescope listening stations.

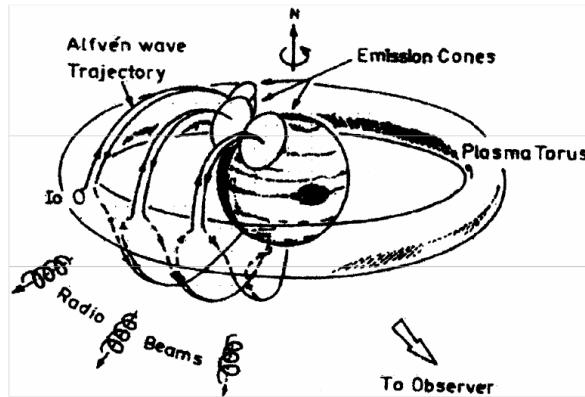


Fig. 4: Alfvén Waves following Io through its orbit and the DAM Emission cones [Bose et al., 2008]

A ground based listening station aiming to record DAM emissions from Jupiter is most likely to succeed between 15-25 MHz [Wilkinson and Kennewell, 1994]. According to ARRL [2000] there is no clear definition of the *shortwave* radio bands however it is most often considered to extend from 3 MHz to 30 MHz. ComReg is the Irish Commission for Communications Regulation within Ireland, and maintains a list of the short wave frequencies which are designated for transmission purposes in Ireland and can be seen in Figure. 5 [Comreg, 2014].

As many commercial short wave radio stations transmit in the lower end of the high frequency (HF) 3-7 MHz range, it can be extremely busy and potentially difficult to monitor DAM emissions where they are strongest. Amateur Radio operators also operate frequently in mid-late HF ranges (*160m, 80m, 60m, 40m, 30m, 20m, 17m, 15m, 12m and 10m bands*) while the higher frequency DAM emissions taper off in strength very quickly. This limits the potential listening

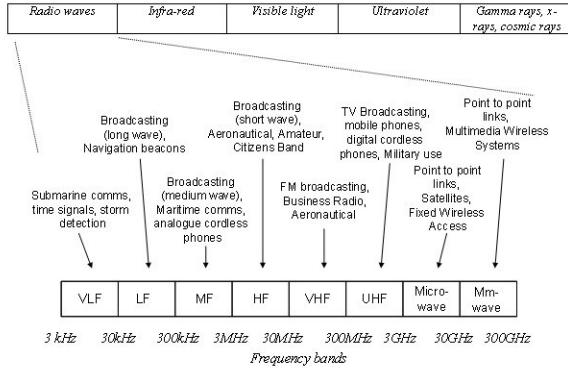


Fig. 5: Irish Regulatory Transmission Ranges [Comreg, 2014]

range significantly. Despite these obstacles, there are sections of the HF spectrum which are suitable to capture Jovian emissions. One frequency to monitor Jovian DAM emissions which is recommended by the Radio Jove project is *20.1 MHz* [NASA, 2012b].

Sourcing a suitable antenna is one of the first requirements to satisfy in order to capture DAM emissions. Antennas are generally best suited to collect electromagnetic radiation at single specific frequencies, but may resonate and therefore operate over a range of frequencies depending on the design [NASA, 2012b]. The wavelength (λ) which corresponds with the frequency (f) *20.1 MHz* can be obtained using the wavelength equation as shown in fig 6. The corresponding wavelength for the frequency *20.1 MHz* works out to be *14.925 m* using this equation.

$$\lambda = \frac{c}{f} \quad (1)$$

$$\lambda = \frac{3 \times 10^8 \text{ m/s}}{20.1 \times 10^6 \text{ Hz}} = 14.925373134328359 \text{ m} \quad (2)$$

Fig. 6: Wavelength Equation

One simple antenna design for collecting DAM emissions is the *dipole*. A dipole antenna can be constructed simply and cheaply from two pieces of wire and three insulators [NASA, 2012b], while ensuring to cut the wires to a length

matching half the desired wavelength being captured [NASA, 2012b]. However as the formula referenced in Figure. 6 describes the use of an *infinitely thin* wire which is not possible in reality, *capacitive end effects* must be taken into account when working out the resonating wavelength for a dipole antenna [NASA, 2012b].

The formula for calculating the resonating frequency for a half wavelength dipole is described in Figure: 7 and produces the value which should measure from tip to tip on the wires used to construct the dipole antenna [NASA, 2012b]. RSGB [2014] states in practice that the true resonance is not exactly multiples of the half-wavelength due to factors such as the coatings on the wire and loss due to radiation. A second formula is detailed in Figure. 8 which takes these factors into account and produces an antenna length which is slightly larger than the formula proposed by [NASA, 2012b]. Formula: 4 n stands for the number of half-wavelengths in the antenna.

$$\left(\frac{\lambda}{2}\right)m = \frac{142.65}{20.1MHz} = 7.097014925373134m \quad (3)$$

Fig. 7: Wavelength Equation for Real World Half Wavelength Dipole Antenna

$$\lambda m = 155\left(\frac{n - 0.05}{f}\right) \quad (4)$$

$$\lambda m = 155\left(\frac{1 - 0.05}{20.1MHz}\right) = 7.325870646766169m \quad (5)$$

Fig. 8: Wavelength Equation for Real World Half Wavelength Wire Antenna

The radio emissions come in several different forms each with slightly different characteristics. Table. 1 shows a list of the more widely known types which can be picked up using ground based listening equipment, and also has some information about their different characteristics [Wilkinson and Kennewell, 1994]. Any particular observation session might be made up of some or all of these different types of DAM emission and can last from a few minutes to several hours for larger noise storms [Wilkinson and Kennewell, 1994].

Type	Emission Length	Emission Description
S-Bursts	short generally 1-10 milliseconds	wideband bursts, several MHz wide
L-Bursts	long 0.5 - 5 seconds	wideband bursts, several MHz wide
N-Bursts	milliseconds upto seconds	narrowband bursts, several kHz wide

Table 1: Most common types of DAM Emissions from Jupiter [Wilkinson and Kennewell, 1994]

Figure. 9 shows an ideal case of the *S-Burst* and *L-Burst* DAM emissions and what they might look like on a frequency spectrum graph. S-Burst emissions are short, generally $1-10 \times 10^{-3}$ s long while L-Bursts can often be between 0.5-5s in length.

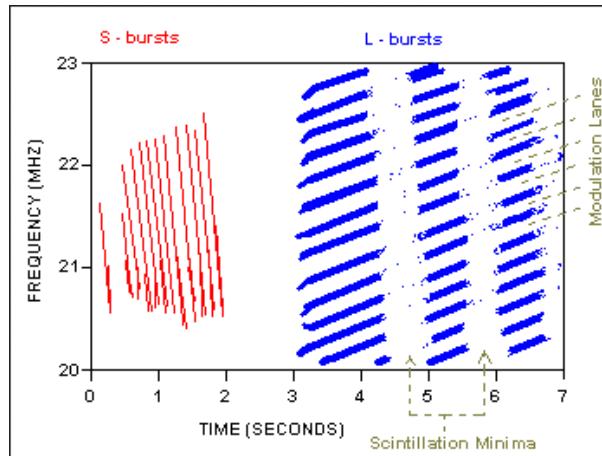


Fig. 9: Ideal DAM Emissions types from Jupiter [Wilkinson and Kennewell, 1994]

Research Hypothesis

The aim of this project is to design and construct a low cost, self sufficient software defined radio (SDR) telescope listening station, which can capture signals for transmission to a central data aggregation point for signal processing and analysis. This telescope should be suitable to study signals in the DAM (10-100 m) band at or near the *20.1 MHz* frequency in order to pick up emissions produced by either Jupiter or the Sun.

There are a number of challenges which need to be overcome to achieve this, such as Jupiter only being visible for a number of months each year and then generally in the evening, night, or morning hours. Often at highly unsociable times. For this reason a radio telescope listening site should be as automated as possible.



Fig. 10: Dual Dipole Antenna Beam at 20FT and 135deg phasing South [NASA, 2012b]

During daylight hours, the ionosphere becomes opaque to signals in the DAM band due to becoming ionised by solar radiation [NASA, 2012a]. The proposed system will have a short window in the order of 1-6 hours every second night and early morning. During which it may be possible to capture DAM emissions

from Jupiter. The Sun is a source of DAM emissions also, and the telescope can capture solar storm emissions without modification, providing the Sun passes through the antenna beam. The telescope may require manual reconfiguration in order to pick up solar storm emissions during the day.

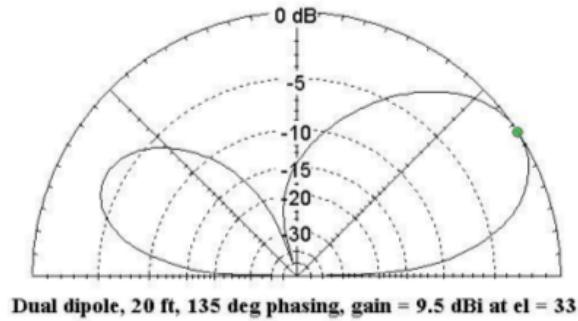


Fig. 11: Dual Dipole Antenna Array Beam[NASA, 2012b]

Interference from human sources such as short wave radio stations or amateur radio operators are also likely to affect the collection of DAM emissions from Jupiter. The ability for automated flagging or removal of interference would be a desirable feature of the system. Lightning storms can also produce interference which will affect observations, it might be desirable for the system to handle natural interference sources also.

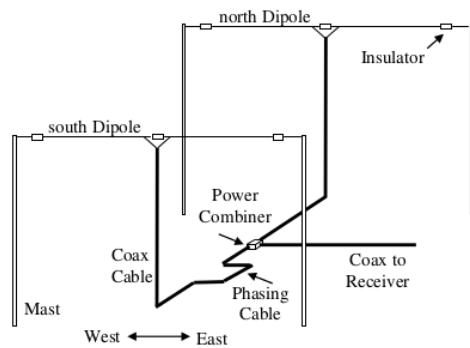


Fig. 12: Dual Dipole Antenna Array [NASA, 2012b]

Methodology

The section aims to provide a summary of the methodologies which will be followed on this project in order to answer the research questions put forward in the next section. It is broke up into the following subsections:

Antenna Build

Building the antenna is further broken down into the following steps:

- source materials to build a dual dipole antenna
- build the telescope antenna
- validate the antenna is capable of collecting signals at or near the 20.1 MHz frequency

Analysis of Listening Site Suitability

Finding a site suitable to deploy the antenna will require a site survey with the antenna connected to a spectrum analyser.

- source a spectrum analyser suitable for performing a site survey
- perform the survey at this site
- repeat until suitable site is found
- deploy the antenna at a site

Data Collection

Jupiter is visible above the horizon at night only during certain periods see Figure. 11. In order to perform the required data collection it is highly desirable to automate the process if possible.

- create listening schedule during which DAM emissions are likely to occur using the Radio Jove software
- develop SDR prototype mechanism for gathering raw data from the antenna

Data Analysis

Collected data can be analysed manually at first in order to validate the testbed, but later using software such as the development of basic algorithms to spot events such as *S-Bursts* occurring in the data.

- analyse data collected for evidence of Jovian or Solar DAM emissions
- analyse data for evidence of interference from human sources
- analyse data for evidence of interference from natural sources

- develop a system which connects to the worldwide dxcluster system and creates flag events for human identified emissions at or near the target frequency being monitored by the telescope
- develop a system which interacts with the Blitzortung servers and creates flag events for emissions generated by lightning

Data Processing

SDR data processing techniques can be developed in order to better filter the signals as they are being collected thereby minimising the level of processing at a later stage.

- using SDR techniques, to reduce interference in data as it is being collected
- attempt to remove instances of human and natural interference using signal processing techniques after collection

Data Aggregation

An API layer allows 3rd parties the ability to access data collected from multiple listening sites and potentially develop new features or systems using the data.

- develop API layer to allow external parties access aggregated data collected by the system

Design Platform

An analysis of the current available IOT technologies and some of the available options which could be used in order to produce an open low cost platform which amateur astronomers could use in order to study emissions in the DAM band.

- design a self sufficient automated platform suitable for collection of signals such as those by the SDR telescope

The SDR hardware transceiver used is likely to be the *HackRF* system while the SDR software components will be developed in either *C++* or *Python* as both languages have bindings for the *GNURadio* development tool-kit [Gnuradio, 2014]. The backend aggregation system with API will most likely be developed in the *Ruby* language as this language is highly expressive and suitable for rapid prototype development. Execution of the Ruby application on the Java VM is

capable using the *JRuby* system, which will also allow the incorporation of any required Java libraries.

Potential Pitfalls

It is difficult to determine at this early stage what will ultimately prove to be the most troublesome element to implement, however there are a number of potential pitfalls which have already been identified.

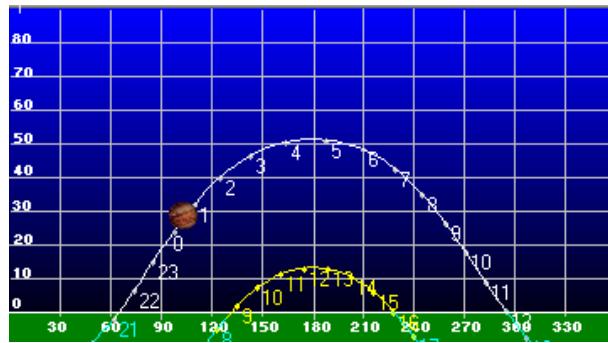


Fig. 13: Radio Jove graph showing Jupiter's max altitude 2014 [Radio-Sky Publishing, 2014]

The latitude of Ireland is 53.3° degrees N. In Ireland Jupiter reaches a maximum altitude of 52° degrees in 2014 see Figure. 13. The telescope configuration which will be documented will apply only to locations at this or a similar latitude. It will be universally applicable at this latitude without modification throughout the world, and with relatively minor modifications to the configuration of the antenna it can be used at all locations. NASA [2012b]

The SDR complexity of the solution required in order to correctly filter interference might ultimately prove too resource intensive to work with a low power system such as the *Raspberry Pi* or *Beaglebone Black*. It might become apparent that the minimum system requirements may need to be increased to an *Intel Atom* powered Netbook for example, or potentially something a lot more powerful such as an *i3* or *i5* system. If this was the case, it will drastically increase the power and cost requirements of the system should it be self sufficient, requiring bigger batteries, more capable/expensive photovoltaic and or wind turbines to keep the system topped up.

Research Questions

The initial research questions which arise are as follows:

1. *What current Internet of Things (IOT) technologies would best suit the development of a software defined radio signal listening station and how cheaply can it be created?*
 - How expensive would a renewable power supply solution such as solar be?
 - Can a low powered computing platform such as the Raspberry Pi B+ suitably host the system, or will a more powerful platform be required?
 - How feasible are wireless technologies such as Zigbee, WIFI or Bluetooth to stream collected data to a central facility?
2. *What processes or algorithms need to be developed to filter or flag known instances of human interference from radio signal observations?*
 - Flag transmission signals identified by amateur radio enthusiasts from a local DXSpider server in recorded data.
 - Flag instances of natural radio interference such as lightning from the Blitzortung server in recorded data.
3. *What SDR tools, processes and or algorithms need to be developed to identify instances of the three main DAM emission types detailed in Table. 1?*
 - Can existing tools and signal processing techniques be employed to find DAM emissions?
 - What is required from an algorithm which might identify DAM emissions within an IQ signal?

Literature Review

The literature review can be broken down into the following areas:

- What are the decametric radio emissions and what are they caused by
- Potential radio telescope designs which could be replicated in order to collect DAM emissions
- Digital signal processing

Decametric Radio Emission what are they and where do they come from?

Belcher [1987] states that the data collected by both *Voyager* spacecraft fit with the Alfvén wing theory as an explanation for the source of the DAM emissions [Belcher, 1987]. Kivelson et al. [1996] discusses the refinements made to this theory to take into account the flowing plasma between Jupiter's ionosphere and the electrically conducting Io. The *Galileo* spacecraft collected data which appears to corroborate the updates to the Alfvén wing model [Kivelson et al., 1996]. Bose et al. [2008] states that the Alfvén waves reflect off Jupiter's ionosphere which cause the DAM emissions to radiate out from the point in Jupiter's ionosphere where it meets the IFT in a cone shape. Imai et al. [2008] proposes an update to this model to take into account the decade long shifts in DAM emission patterns, and proposes an extension to the emission cone model to include a *searchlight* shaped emission zone [Imai et al., 2008] see Figure. 44.

Radio Telescope Designs, Which to Choose?

The NASA project *Radio Jove* recommended the dual dipole array design for a cheap low cost listening site as shown in Figure. 12 [NASA, 2012b]. But it is by no means the only antenna design which would be capable of picking up the DAM emissions. Wilkinson and Kennewell [1994] recommends a slightly more advanced design, the *folded dipole* which maximises the bandwidth available to the antenna [Wilkinson and Kennewell, 1994]. Greef [2012] details a third alternative for collecting DAM emissions, a shortwave loop antenna as can be seen in Figures. 46a, 46b and 46c.

Digital Signal Processing

Smith [2003a] explains that digital signal processing is a term used to describe the mathematics, algorithms and techniques used to manipulate signals after they have been converted from analogue to digital. Freidt [2013] holds that digital signal processing is the preferred means to process signals, for reasons such as stability and for its resistance to long term ageing effects that analogue systems suffer from. However as Smith [2003b] points out, due to the nature of the conversion from analogue to digital, information is lost in this process. Smith [2003b] maintains that the proper sampling of an analogue signal occurred if you can reconstruct the signal from the digital samples collected, and incorrect sampling will lead to loss of the original signal due to aliasing.

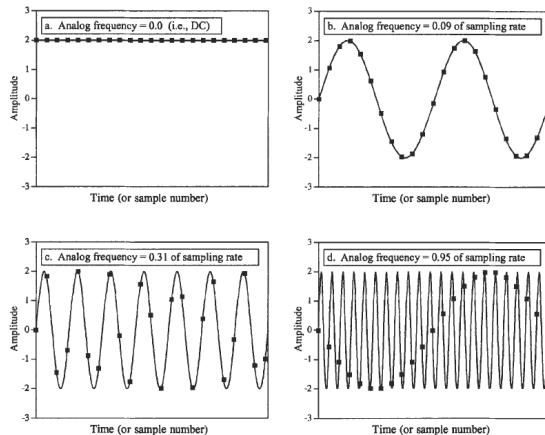


Fig. 14: Sampling an Analogue Signal [Smith, 2003b]

Smith [2003b] demonstrates in Figure: 14 how signal data loss occurs due to aliasing. When sampling an analogue signal which has a frequency more than half of the sample rate (Nyquist frequency), Smith [2003b] observes that the original signal cannot be reconstructed. This is referred to as the sampling theorem [Smith, 2003b] where f_s is the sample rate and f is the frequency being sampled.

Ossmann [2015b] contends that the application of Nyquist-Shannon sampling theorem only applies to real analogue signals where the bandwidth is equal to half the sample rate. However for a complex digital signal the bandwidth is equal to the sample rate [Ossmann, 2015b].

$$f_s > 2f \quad (6)$$

Fig. 15: Sampling Theorem aka Nyquist-Shannon sampling theorem [Smith, 2003b]

Due to the cheap availability of computational resources, digital signal processing is capable of being carried out now within software entirely, this has led to the development of software defined radio solutions [Freidt, 2013]. The GNU-Radio software allows creation of software defined radio solutions by replacing hardware functions with modular software functions. These software functions are capable of being connected together, an output from one function providing input for another. It is in this fashion it is possible to transform digital signals using digital signal processing methods within the GNURadio platform[Gnuradio, 2014].

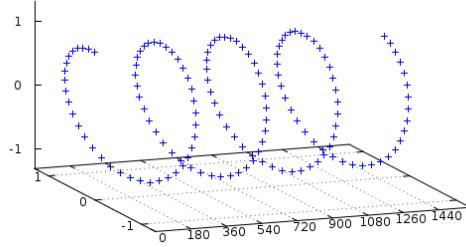


Fig. 16: I/Q Samples Helix [Kuisma, 2014]

Ossmann [2015a] illustrates how the HackRF One SDR transceiver can be accessed within GNURadio by way of the osmocomm source which is an abstraction layer between GNURadio and the HackRF driver. Figure: 48a shows an amplitude modulation signal which has been digitally sampled. In order to demodulate such a signal, an understanding how the signal data is stored is a must. Digital periodic signal samples tend to be stored in a complex format which amounts to polar coordinates [Ossmann, 2015c]. I is the point on the real axis, and Q is an angle which contains the imaginary component. See Figure: 16

shows how these I/Q values are plotted periodically and Figure: 17 shows the I/Q polar data Kuisma [2014].

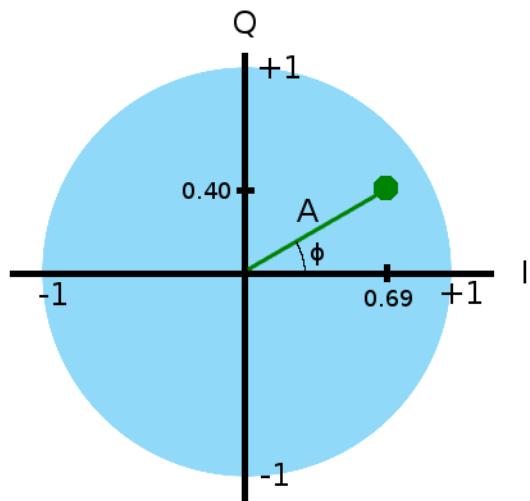


Fig. 17: I/Q Samples Polar Plot [Kuisma, 2014]

Topic	Belcher 1987	Kivelson et al 1996	Bose et al 2008	Imai et al 2008
What are the Jovian DAM emissions and what causes them?	Large fraction of DAM emissions come from point where IFT meets Jupiter's ionosphere (p3). Large moving conductor within a magnetised plasma (p1) produces Alfvén wing.	Alfvénic disturbances, generated by flowing plasma from Jovian magnetosphere and conducting Io (p337).	Alfvén waves reflecting off Jupiter's Ionosphere (p79).	Not fully understood, but believed to be produced by cyclotron maser instability [Imai et al., 2008].
Topic	Wilkinson et al 1994	NASA Radio Jove 2012	Greef 2012	
Radio telescope designs suitable to capture DAM emissions from Jupiter	Wilkinson et al suggest a folded dipole antenna design	Radio Jove project suggest a dual dipole antenna	Greef demonstrates a low cost Loop Antenna design with reflection plate	
Topic	Smith 2003	Freidt 2013	GNU Radio 2014	Ossmann 2015
Digital signal processing	Smith argues digital signal processing is one of the most powerful technologies that will shape the 21st century.	Freidt states digital signal processing now ubiquitous, and cheap availability of computational power lends self to software defined radio solutions.	GNURadio allows digital signal processing using transformation functions developed in software.	Ossmann argues that the HackRF One is perfectly suited as a low cost wide range transceiver for use within software defined radio prototypes.

Table 2: Literature Review Synthesis Matrix

Testbed Build and Verification

The NASA Radio Jove dual dipole antenna design (Figure: 12) was chosen over the other designs for a number of reasons, namely:

- Simplicity of the architecture and consequently also construction
- Low cost of building materials
- Reasonably effective performance (5-9 dB gain depending on configuration)
- Easy to operate and maintain
- Suitable for a permanent installation
- Large body of technical documentation supporting the operation

Special Resources Required

The following resources have been identified as being required in order to perform the research and are listed as follows:

GnuRadio

The GnuRadio software is an open-source software development tool kit that allows access to signal processing techniques in order to implement software radio solutions.

HackRF

The HackRF SDR transceiver system is the software defined radio transceiver chosen for the prototype system.

PL259 / SO239

Cable adapters which connect coax cables together with the dipole center.

Radio Jove Software

The Radio Jove software is extremely useful for observers wishing to capture DAM emissions from Jupiter. It contains a large number of features such as emission prediction observation charts, and information regarding Jupiter's location in the sky from any specified point on the Earth's surface.

RG59 Coax

RG59 coax cable is required to link the dipole antennas back to the SDR transceiver.

Spectrum Analyser

A spectrum analyser will be required in order to perform a site survey to determine if a location is suitable for collecting DAM emissions.

Antenna Build

In order to satisfy the main requirement of capturing DAM signals at 20.1MHz construction of an antenna was needed. The equation shown in Figure: 8 was used to calculate a starting estimate of the length of antenna wire required to construct this antenna. Many factors can affect the ability of an antenna to receive data at a particular frequency [ARRL, 2000], such as the following:

- quality of the wire conductor or thickness of the wire
- height that the antenna is mounted above the ground
- capacitive end effects
- closeness to radio conductors

One simple method of partly improving antenna performance is by controlling the length of the antenna wire while measuring the Standing Wave Ratio (SWR) value, which is the ratio of the maximum peak voltage anywhere on a line to the minimum value at any point along the same line. The use of a SWR analyser becomes invaluable in this process.



Fig. 18: Measuring the SWR of the antenna with an SWR Analyser

The initial length of antenna wire was cut to match the length produced by the equation in Figure: 8 and was then cut in half before each end was connected to a dipole centre. The antenna was placed on the ground before being connected to the SWR analyser. The SWR value for the antenna was measured, and it was discovered the antenna was suitable for capturing of signals at 18 MHz. The antenna was then shortened by a small identical amount on each side and the

SWR values were again measured until the antenna registered as being most suitable for operation at 20.1MHz as seen in Figure: 18.

The SWR equations shown in Figure: 19 $|\rho|$ is the reflection coefficient, P_f is the power in the forward wave entering the antenna while P_r is the power of the reflected wave in the antenna [ARRL, 2000].

$$SWR = \frac{1 + |\rho|}{1 - |\rho|} \quad (7)$$

$$|\rho| = \frac{SWR - 1}{SWR + 1} \quad (8)$$

$$|\rho| = \sqrt{\frac{P_r}{P_f}} \quad (9)$$

Fig. 19: Standing Wave Ratio Equations

$$|\rho| = \frac{1.2 - 1}{1.2 + 1} \quad (10)$$

$$|\rho| = 0.0909090909090909088 \quad (11)$$

$$0.0909090909090909088 = \sqrt{\frac{P_r}{100}} \quad (12)$$

$$0.0909090909090909088^2 = \frac{P_r}{100} \quad (13)$$

$$P_r = 0.826446280991735 \quad (14)$$

Fig. 20: Calculating P_r for the antenna

The value of SWR for the antenna should be ideally as close as possible to 1, this ensures all the signal energy collected by the antenna is transferred to the load successfully. However in practice this is never the case as all antennas have varying amounts of loss. The antenna once mounted had a measured SWR value of 1.2 which equates to a P_r value as shown in Figure: 20 of 0.826446280991735 which is a loss of 17.35% or about 1dB which is considered reasonable [ARRL, 2000].

Table: 3 gives a breakdown of the costs associated with the antenna build to date.

Item Name	Cost (€)
100m Copper Wire	20.00
100m Coax RG59	25.00
2 × Dipole Centers	20.00
8 × PL259	18.00
2 × SO239	4.00
SMA-SO239 Adapter	4.50
2 × SO239-SO239 Adapter	4.50
T Adapter	3.00
Patch Lead	5.00
2 × 4m 5cm Pipe	15.00
2 × 4m 4cm Pipe	15.00
HackRF Transceiver	315.00
RTL DAB Receiver	25.00
MCX-SO239 Adapter	6.50
Total	480.00

Table 3: Antenna Build Cost



Fig. 21: Dual Dipole Antenna Deployment

Listening Site Suitability

A convenient location for the antenna deployment was selected and the antenna was deployed. It was necessary to determine if this site was in fact a suitable location to host a radio telescope antenna. In order measure the ambient noise at the site, a Tektronics SA2600 spectrum analyser was connected to the antenna and left for 2 hours at midday to gather data. The spectrum is likely to be full of radio interference from human and natural sources at this time. The results can be seen in Figure: 22. The ambient RF noise at the site was quite high, ranging between -80dB and -70dB on average.

Similar readings were taken using the HackRF while attached to the antenna as show in Figure: 23. The measurements recorded with the HackRF were performed using the *gqrx* SDR software while all amplification settings inside *gqrx* were set at 0, in order to get an accurate reading on the raw signal being collected by the antenna. The values were on average -20dB quieter than those recorded by the SA2600 spectrum analyser, this points towards an inherent deafness flaw in the HackRF design itself, and possibly the requirement of a pre-amplifier (preampl) in order to boost the gain on the input signal.

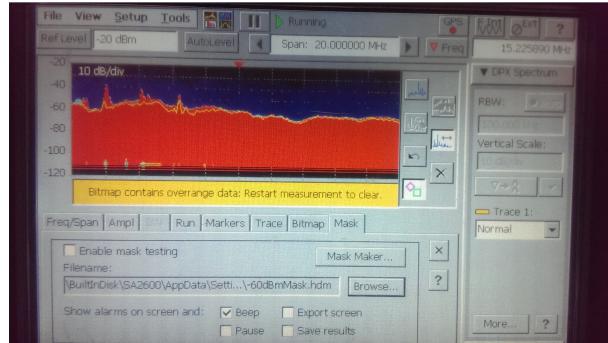


Fig. 22: Site Survey performed using a Tektronics SA2600 Spectrum Analyser

In May 2013, the Solar Physics Group from Trinity College Dublin, performed a site survey at Birr Castle to ascertain the suitability of the site for an installation of the Low Frequency Array (LOFAR) telescope [McCauley, 2013]. The study was focused on a wide range of frequencies between 10 and 400MHz, a portion of which can be seen in Figure: 24. The report concluded that the

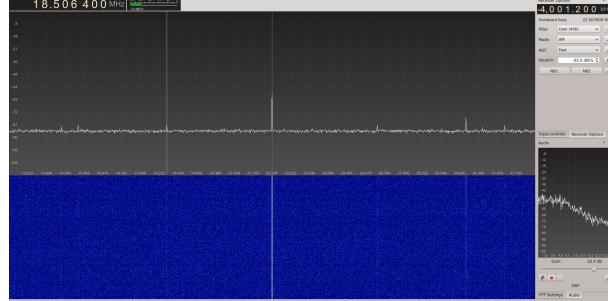


Fig. 23: Site Survey performed using HackRF One

location at Birr Castle was a relatively quiet location as compared against a site at Bornim, Germany and another at Bleien, Switzerland.

From the results of this survey, it can be seen that the average background noise levels were about -55dB near 20MHz which is similar to those recorded 80km away at the Kilkenny site. Table: 4 details the results collected at the Kilkenny site and includes those performed by the Solar Physics Group at Birr Castle for comparison. Results indicate the Kilkenny site appears to be a reasonable location at which to host the radio telescope.

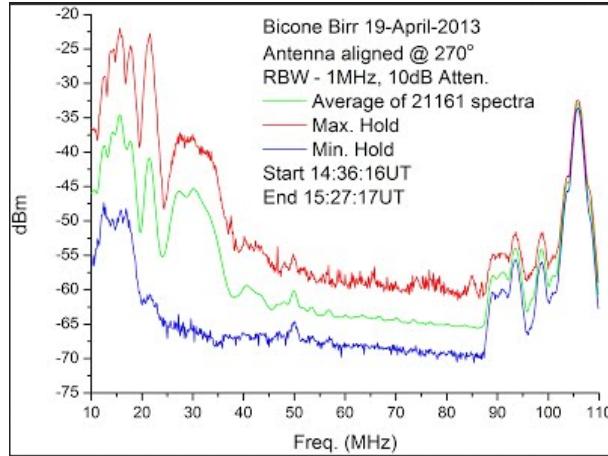


Fig. 24: LOFAR Site Suitability Survey performed at Birr Castle [McCauley, 2013]

Site	Equipment	Average Noise at 20.1MHz
Kilkenny	Tektronix SA2600 20.1MHz Dipole	-65dB
Kilkenny	HackRF One 20.1MHz Dipole	-65dB
Birr	LOFAR Array 10-100MHz Schwarzbeck Bicone	-55dB

Table 4: Average Noise Measurements at Kilkenny Listening Site compared to Birr Listening Site [McCauley, 2013]

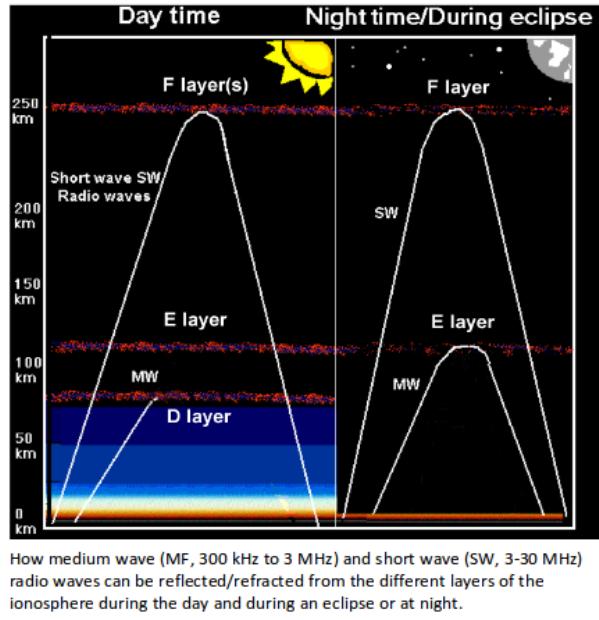
Verification of the Radio Receiver

An opportunity to validate the HackRF transceiver arose with the announcement of a public Medium Wave (MW) experiment by Nichols [2015a] of the Radio Society of Great Britain (RSGB). The RSGB Propagation Studies Committee intended to perform an experiment during the partial solar eclipse on 20th March 2015. As can be seen in Figure: 49, the UK and Ireland would witness more than 90% totality during the eclipse. This was an opportunity to perform simple experiments to demonstrate the Sun's effect on Earth's ionosphere, and how this ionisation affects the propagation of radio signals.

According to Nichols [2015b], MW radio stations which are located more than 500 km away are unlikely to be propagated during daylight hours due to their signals being absorbed by the D layer as shown in Figure: 25. However this D layer does not exist during night time hours, as a result these radio signals are free to reflect from the E and F layers. Nichols [2015a] states that this is also true during a solar eclipse with a high totality percentage as would occur on the 20th March 2015.

Nichols [2015a] provided some a number of radio stations which transmit signals in the MW range at various locations in the United Kingdom, Europe and also a number in Iceland. The experiment called for choosing a station which is transmitting in the MW range and is capable of being heard at the listeners location during the night time. This station should not be capable of being heard during the day time, the experiment called for a station which is further away than 500 km. The chosen radio station should then be tuned in to coincide with the beginning of the solar eclipse. The station receive power should be plotted against time. It was expected that the signal strength of the radio station should rise to a maximum which coincided with the solar eclipse maximum.

It was immediately apparent that the RadioJove antenna design would not be suitable for this experiment, and a suitable alternative was examined. Dur-



How medium wave (MF, 300 kHz to 3 MHz) and short wave (SW, 3-30 MHz) radio waves can be reflected/refracted from the different layers of the ionosphere during the day and during an eclipse or at night.

Fig. 25: Comparing propagation of MW radio signals during day and during night/solar eclipse [Nichols, 2015a]

ing the initial research into potential designs a paper by Litva and Rook [1976] mentioned the use of a Beverage antenna for use in highly directional receivers such as early transatlantic radio communication experiments. Due to the simple nature of the Beverage antenna design, this was considered for use in this experiment.

Methodology

The following methodology was followed during this experiment:

1. The dipole antenna built for use in the main part of the dissertation was not best suited for picking up signals in the MW range so an alternative design was chosen.
2. A Beverage antenna was picked as it was easily aimed and had a simple design. The antenna very simply consisted of a copper wire 80 m long attached to a long wire antenna terminator which had an SO239 connector [Litva and Rook, 1976].

3. The listening site was longest in the East-West axis, and having the receiver positioned at the far west end of the site was most convenient. For this reason a radio station situation in an Easterly direction was picked.
4. The antenna was aimed in the general direction of the radio station chosen, and simply placed on the ground.
5. HackRF was tuned to the chosen radio station.
6. 2 MHz bandwidth of the spectrum was recorded during the entire length of the solar eclipse, the signal strength of the radio station can be plotted against time at a later date using this recorded data.
7. The SDR receiver should have the automatic gain control switch off in order to get accurate power results.

The chosen radio station was *Radio China International* (1.440 MHz) which was a powerful signal during the night time despite it being transmitted from Marnach in Luxembourg which is 950 km away from the listening site. Once the solar eclipse began, the HackRF SDR receiver was tuned to 1.440 MHz with a bandwidth of 2MHz and IQ samples were recorded. As the eclipse neared 20% totality, the radio station began to emerge from the background noise at -55 dB. The signal rose steadily until the eclipse maximum point which was -28 dB, and then averaged at a level of -45dB as the totality value dropped. At 20% of eclipse totality, the station faded once more before disappearing into the background noise level at -55dB. The results were plotted in Figure: 26 and were submitted to Nichols [2015a] for inclusion in the overall experiment.

A number of issues with the HackRF SDR transceiver were discovered during this experiment. The technical specifications show the operating range of the HackRF to be 10 MHz - 6 GHz [Ossmann, 2015d]. In practice it possible to tune to frequencies below 4 MHz, even as low as 500kHz with a few caveats.

Reliable tuning proved a problem below 10MHz, when the HackRF was power cycled, tuning to the same frequency in software would see the station vanish. It took trial and error find it once more by scanning lower and higher until the station was reacquired. This is due to the internal signal oscillator being affected by many external variables such as temperature. To be certain of the exact frequency being monitored, an external clock source must be used to provide a signal reference to the system.

The HackRF also appears to be quite deaf without maxing the IF and RF amplifiers. While this could be solved by adding a preamp at the antenna, such

a step would also increase the level of background noise which might defeat the purpose.

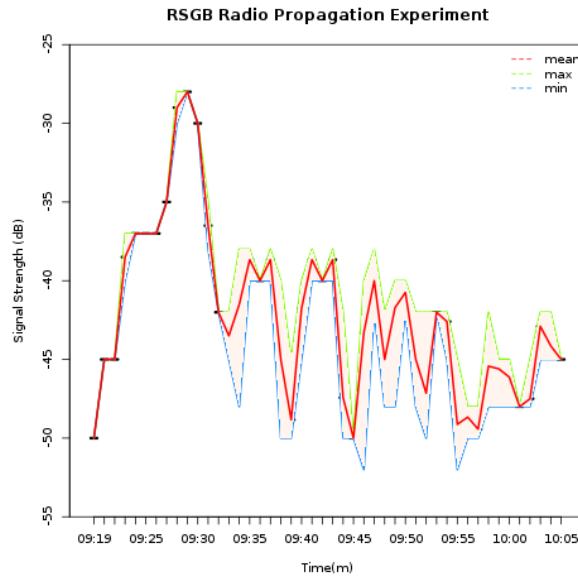


Fig. 26: Plot of signal power vs time during 20th March 2015 solar eclipse

Capturing DAM Emissions

Using the Radio Jupiter Pro software, a prediction was made that 23rd April 2015 would offer a very good opportunity to hear DAM emissions. As can be seen in Figure: 27a, at the point of the highest chance of capturing DAM emissions, Jupiter was right on the very edge of the antenna beam focus. Due to the limitations in the design of the antenna, this configuration offered the best chance to receive an emission from Jupiter.

Despite this, a number of emissions were recorded as can be seen in the raw image Figure: 27b. The emissions appear as faint horizontal lines in this waterfall diagram. This diagram is limited by the small bandwidth of 2 MHz and short period of 2 minutes. Ideally in order to spot these interesting emissions a large bandwidth of 20 MHz for instance should be used, over a long period of observation such as 1-24 hours. An example of this is section of a spectrogram seen in Figure: 27c, which shows averaged signal power data for frequencies 17-55 MHz and 70-1000 MHz for a 24 hour period.

There are many open source software tools such as `rtl_power`, `simple_ra` and `heatmap` which could capture averaged raw signal strength data from a RTL based receiver in order to build spectrogram diagrams. Unfortunately most of this software is not compatible with the HackRF. However the basic functionality from these tools can be replicated using basic processing blocks within GNURadio and the spectrograms can be built using tools like Octave or Matlab.

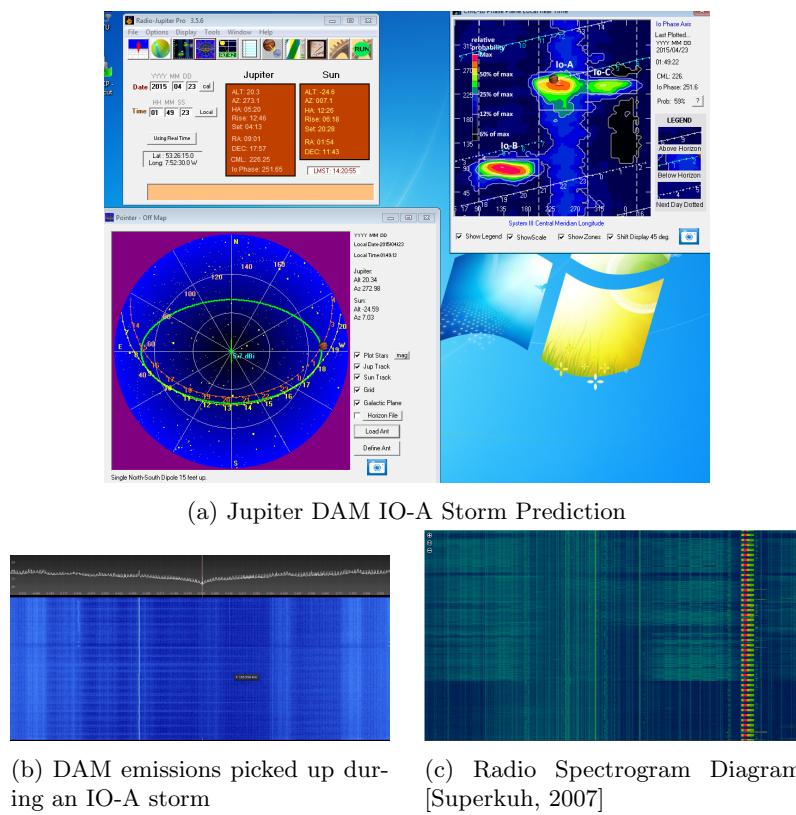


Fig. 27: DAM Emissions

Research Question 1

What current Internet of Things (IOT) technologies would best suit the development of a software defined radio signal listening station and how cheaply can it be created?

- How expensive would a renewable power supply solution such as solar be?
- Can a low powered computing platform such as the Raspberry Pi B+ suitably host the system, or will a more powerful platform be required?
- How feasible are wireless technologies such as Zigbee, WIFI or Bluetooth to stream collected data to a central facility?

Determine SDRT Power Requirements

A major component of designing a self sufficient system is choosing the power supply. One solution is the use of renewable sources such as wind or solar to create energy and the use of batteries to act as a buffer and storage of this energy. When a suitably large battery array is deployed, power to the system can be provided during periods when there is no sunshine or wind available.

In order to design a self sufficient listening site it was necessary to firstly determine the power requirements of the hardware essential to the functioning of the system. If there are high computational requirements the system will generally also have high power needs, which can have a drastic effect on the cost of implementing a sustainable power supply using renewables. It is prudent therefore to implement the system as cheaply as possible, and using low powered devices.

The SDR RTL and HackRF receivers require a minimum of a USB 2.0 interface and computational requirements for processing data which immediately reduced the potential platforms to devices such as the Raspberry Pi B+, Raspberry Pi B2 and the Intel Atom or better.

Bryce [2011]

Methodology

The following platforms were chosen for testing purposes as they initially appear to meet or exceed the minimum requirements of operating *rtl_power* while also building spectrograms from the recorded data using *heatmap.py*:

1. Raspberry Pi B+ 800MHz, 512MB RAM
2. Raspberry Pi B 2. 900MHz, 1GB RAM
3. EEEPC Intel Atom N550 Netbook. 1.55GHz, 2GB RAM

Each platform would be tested on the following metrics:

Idle

The power usage while the system is at rest

heatmap.py

The power usage while the system is building spectrogram with heatmap.py

rtl_power

The power usage while the system is collecting data with rtl_power

Both heatmap.py and rtl_power

The power usage while the system is building spectrogram with heatmap.py and collecting data with rtl_power

100% CPU Load

The power usage while the system is at 100% load

The power usage of each system was measured using a power meter and the results were plotted as shown in Figures: 28a, 28b, and 28c.

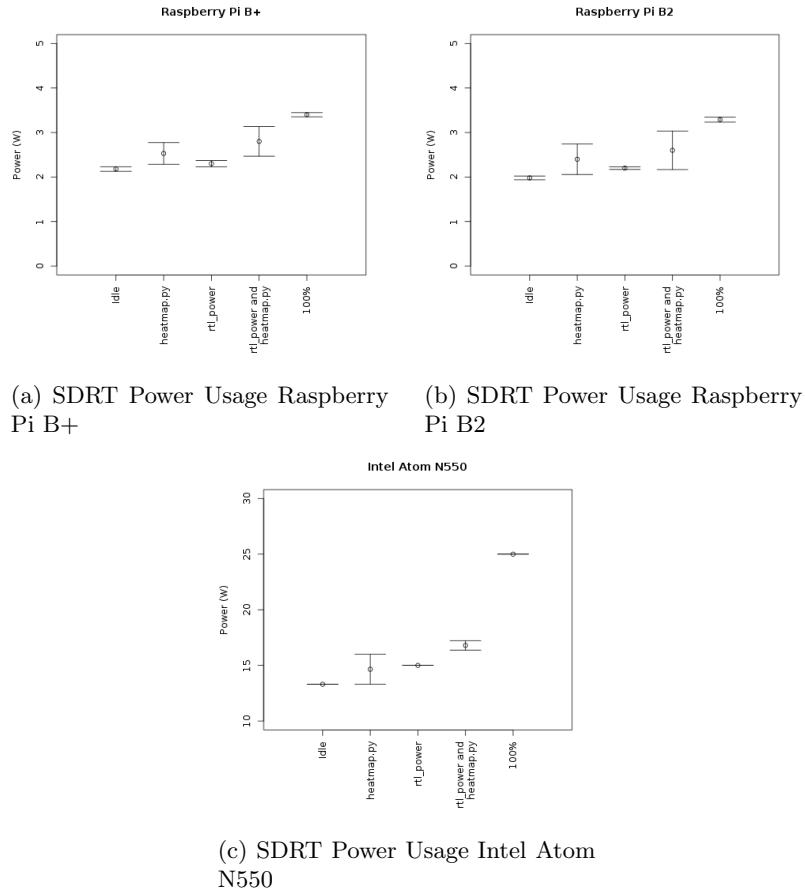


Fig. 28: DAM Emissions

Using solar data collected by the national weather service, MET Eireann [MET, 2015] and [ECA&D, 2015], a series of plots were produced to aid in the calculation of the battery array capacity required to power the system. As can be seen in the Figure: 31b, the mean number of hours of sunlight for the year was calculated to be $\mu = 4.446$, with a minimum of 1 hour and a maximum of 9.156 hours.

$$Power(Watts) = Current(Ampere) \times Voltage(V) \quad (15)$$

$$A = \frac{W}{V} \quad (16)$$

$$A = \frac{25}{12} \quad (17)$$

$$Ampere = 2.08333333A \quad (18)$$

Fig. 29: Calculating Amps using Watts and Voltage

Solar Panels generally operate at either 12 or 24V, and when coupled with a battery charge controller, can be used to safely recharge batteries using generated power. The load power value measured previously for the Intel N550 Netbook operating at 100% was 25W. Taking the load and the assumed voltage value of 12V, the load current was generated using the power equation shown in Equation: 29. The current required to generate 25W at 12V is 2.08333333A.

An initial estimate of 48 hours of power capacity was made to ensure the system can be powered for an extended period during periods of low solar activity. A plot of load vs battery capacity was generated as shown in Figure: 31a. This plot shows the capacity value required to satisfy a 25W load at 12V for a 48 hour period is about 100Ah.

Figure: 31b shows the averaged daily hours of sunshine over a 15 year period. This plot demonstrates that for half the year the sun shines for between 1 and 4 hours each day. This is a major limiting factor in creating a self sufficient solar powered system, as batteries may only be charged during periods of sunshine. During the times of the year with daily sunshine hours below the mean, a larger battery capacity is required in order to continue to power the system during days with little sunshine. Correspondingly, as the sunshine hours fall, a larger

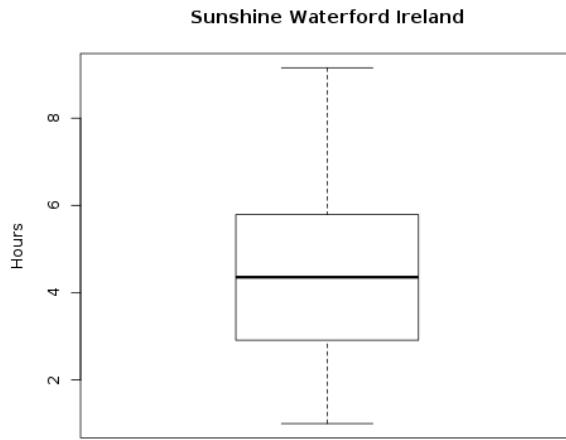


Fig. 30: Average Daily Sunshine in Waterford

solar panel is required to ensure as much light as possible is converted to energy storage.

Next a plot of solar panel power output vs time taken to charge a 100Ah battery was generated as Figure: 31c. This plot shows that in order to reliably charge a battery of size 100Ah in a single day which has the mean hours of sunshine the system will require a solar panel array of at least 350W.

The measurements were repeated for the Raspberry Pi systems. The power demands were rounded up to 5W which produced a battery capacity of 20Ah to power for 48 hours. The results were then tabulated as shown in Table: 5. The components required to implement a solar powered system such as the panels, batteries, charge controller and AC/DC inverters were priced and the results were included in this table also. Price wise, having a Raspberry Pi system in the listening station would make for a cost effective solution. As both the B+ and the B2 versions operate with the very low power usage of 5W, the solar renewable solution would be cheapest also at an estimated €150 for the solar power components.

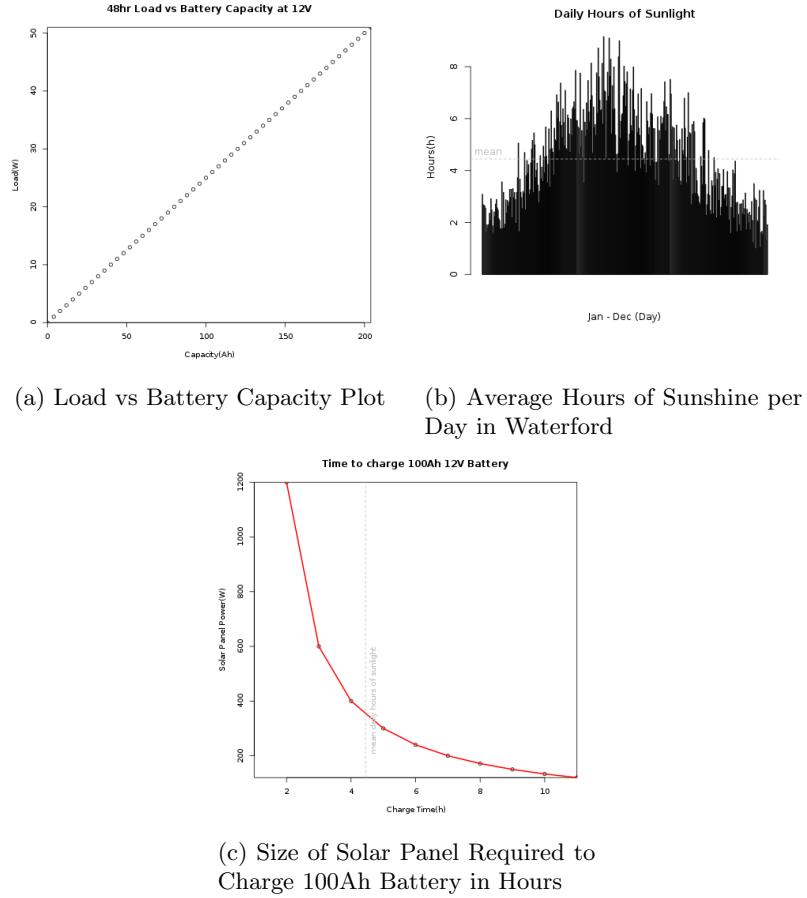


Fig. 31: Solar Plots

Equipment	Solar Panel Power(W)	Battery Capacity(Ah)	Estimated Cost(€)
Raspberry Pi B+	75	20	150
Raspberry Pi B2	75	20	150
Intel Atom N550	350	100	500

Table 5: System Power Requirements

Determine SDRT Computational Power Requirements

The aim of this experiment was to determine the minimal hardware which was computationally capable of collecting data, while performing any data analytical or processing tasks required by the system.

Methodology

The following platforms were chosen for testing purposes as they initially appear to meet or exceed the minimum requirements of operating *rtl_power* while also building spectrograms from the recorded data using *heatmap.py*:

1. Raspberry Pi B+.
2. Raspberry Pi B 2.
3. EEEPC Intel Atom N550 Netbook.
4. Intel i5-3340M 2.7GHz

Each platform would be measured under a single metric, namely the length of time it takes to produce a spectrogram from data collected over a 24 hour period. Table: 6 shows the results gathered on each platform. As the time taken to process the spectrogram was longer than 24 hours for both Raspberry Pi models tested, they could not be considered capable of hosting the SDRT system and so this particular test was aborted when the time exceeded 24 hours for both Pi models.

The Intel Atom powered Netbook performed considerably better with a result of 4.12 hours. This would allow the collection of data, while also the sustainable processing of the previous days data without becoming overloaded.

Equipment	Generate Spectrogram(h)
Raspberry Pi B+ 800MHz 1 Core	24Hrs+
Raspberry Pi B2 900MHz 4 Core	24Hrs+
Intel Atom N550 1.55GHz 2 Core	4.12hours
Intel i5-3340M 2.7GHz 2 Core	0.25hours

Table 6: System CPU Power Requirements

Determine SDRT Network Connectivity Requirements

The aim of this experiment was to determine the optimal networking technology to transfer collected and or processed data from the SDRT to another system.

Methodology

The following technologies were investigated during this experiment:

1. Zigbee (XBEE Pro 2B 802.15.4)
2. WIFI (802.11N)
3. Fast Ethernet (802.3u)
4. Gigabit Ethernet (802.3-2008)

Each technology was measured using a single metric, transfer speed to copy 2GB of collected data between two nodes in the network. Table: 7 shows the results obtained.

Technology	Bitrate	Est(s)	Result(s)
Zigbee	250kbit/s	76,000	24Hrs+
WIFI N	144Mbit/s	132	737
Fast Ethernet	100Mbit/s	181	904
Gigabit Ethernet	1Gbit/s	30	45

Table 7: Networking technologies transferring 2GB data

There existed a large discrepancy between the estimated values and the actual measurements obtained for several technologies measured. A number of factors could account for this, such as the estimated values being generated using theoretical maximum bandwidth for the technology, which are unrealistic for real world applications.

One example is the underlying hardware which handles both the USB and the Fast Ethernet network interfaces on the Raspberry Pi systems has a limit of 2Mbit/s, and could therefore never reach the theoretical maximum of 11Mbit/s suggested by Fast Ethernet. Using the Zigbee XBEE 802.15.4 modules, the theoretical estimate of 250kbit/s suggested a time of 21 hours to transfer 2GB of data, however after 24 hours the transfer was still ongoing. As the ability to the

collected data must be faster than the time taken to collect it, the Zigbee test was cancelled after 24 hours. The results show WIFI, and Ethernet technologies being preferable in this instance.

Research Question 2

What processes or algorithms need to be developed to filter or flag known instances of human interference from radio signal observations?

- Flag transmission signals identified by amateur radio enthusiasts from a local DXSpider server in recorded data.
- Flag instances of natural radio interference such as lightning from the Blitzortung server in recorded data.

Flag Amateur Radio Enthusiast Transmissions

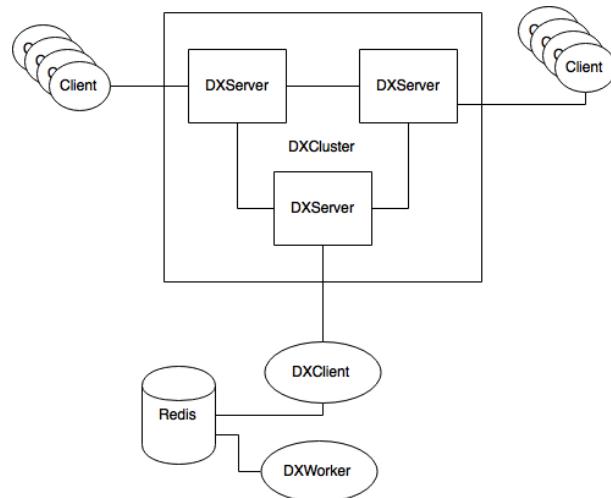


Fig. 32: DXCluster Client Architecture

A DX server is a system which Amateur (Ham) Radio operators may use in order to inform one another in real time, about instances of radio signal transmissions from DX stations and other amateur radio stations. These DX Servers are often connected together to form a cluster. This allows many users from all over the world to communicate and share this information by connecting to the cluster. It is a rich source of identified human transmissions which often

have the time, location and signal frequencies which were recorded. The data being shared is also often rigidly structured which greatly simplifies the task of implementing a software parsing solution [Koopman, 2007]. Table: 8 details the format of each packet of information shared on the DXCluster.

Key	Sample Value
Call Sign of Spotter	DX de EA1MX:
Frequency	144364.0
DX Call Sign	TM64TDF
Comment	IN73XK<TR>IN93OA tnx qso
Time	1623Z

Table 8: Sample DXSpider Data Packet

A software client was developed in order to connect to a local server within the DXCluster. The architecture diagram is shown in Figure: 32. It was designed to gather all data from the cluster while filtering transmissions outside the frequency range currently being monitored by the telescope, and also filtering transmissions outside Europe. All signals which have been identified as being within the range being monitored, would be flagged and all related meta data for each transmission would be stored for processing at a later stage.

Methodology

The aim of this experiment was to record 24 hours worth of data on the DXCluster for signals originating in Europe within the frequency range being monitored by the SDRT system. The following methodology was followed during this experiment:

1. Collect 24 hours worth of data using the DXCluster Client developed
2. Filter out all signals not originating in Europe
3. Filter out all signals outside the target range of 18 MHz - 40 MHz

The experiment was run for 24 hours, and during this time, 1984 transmissions were recorded on the DXCluster. The data was filtered to only save transmissions originating from European countries, and also filtered further to only contain transmissions within the range being monitored by the SDRT namely

18 MHz - 40 MHz. This reduced the number of transmissions recorded to 209. The Figure: 33a shows a high level breakdown of the most popular countries for which transmissions originated from during the 24 hour period of monitoring. Figure 33b shows this same data broken down by the hour it was collected and finally Figure: 33c shows this same data broken down by the radio frequency on which the transmission originated. As Figure: 33c demonstrates, the majority of signals appear within narrow bands as is to be expected, as amateur radio enthusiasts operate in bands such as the 10M band for instance which corresponds with a frequency range of 28.000 MHz - 29.700 MHz, and then within channels inside this range.

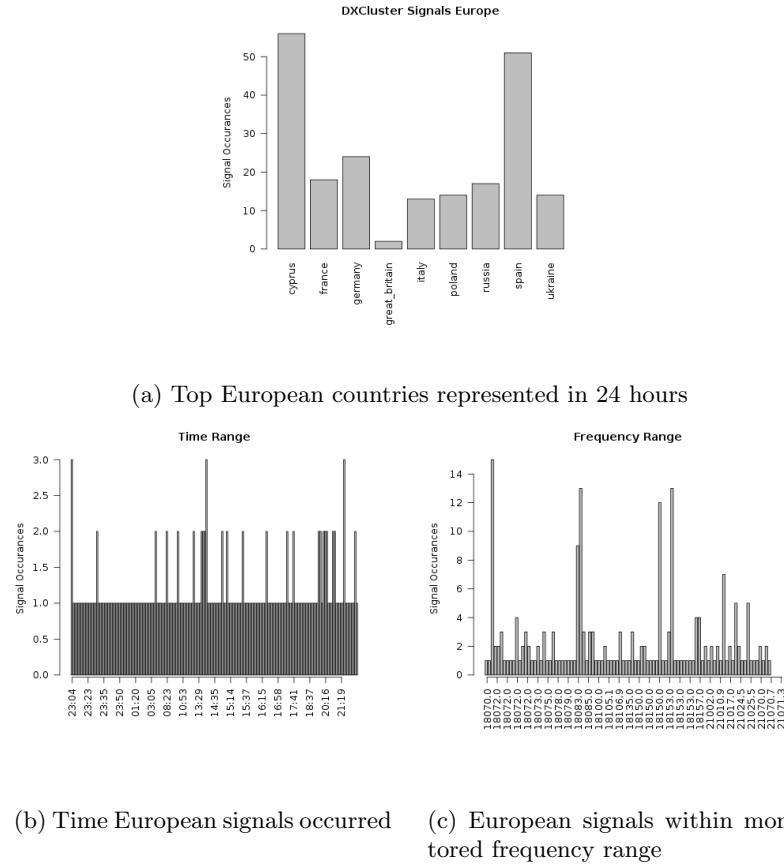


Fig. 33: DXCluster data

Flag Natural Emission Sources

The Blitzortung project operates an online service which displays global information about instances of lightning strikes in real time. Wanke et al. [2014] provide the designs for a listening station which amateur enthusiasts can then build and operate. Each site can share information collected on local instances of lightning with the central server in real time [Wanke et al., 2014]. A software client was developed which can retrieve data on lightning strike occurrences from within Europe in 10 minute blocks from the Blitzortung server. Table: 9 details the format of each Blitzortung data packet.

Key	Sample Value
Date	2015-08-03
Time	21:40:03.600511018
Latitude, Longitude,	
Elevation	pos;43.899106;20.438919;0
Unknown	str;0
Station ID	dev;14497
Confirming Stations	sta;11;24;951,956,1313,1171,803

Table 9: Sample Blitzortung Data Packet

The Haversine function shown in Figure: 34 provides the means to determine the distance between two points on a spherical surface, which Earth approximately is [Pineda-Krch, 2010]. In this function, φ corresponds with latitude, λ corresponds with longitude and R is the radius of the Earth. This function is used to measure the distance between the location of the SDRT listening site and each individual lightning strike data point. With this distance value, it is then possible to discard data points which originate further from the SDRT listening site than a chosen value such as 1000km.

Methodology

The following methodology was followed during this experiment:

1. Collect 10 minutes of data using the Blitzortung Client developed
2. Filter out all lightning strikes not originating in Europe
3. Filter out all lightning strikes outside the target range of 1000km

$$a = \sin^2\left(\frac{\Delta\varphi}{2}\right) + \cos(\varphi_1) \times \cos(\varphi_2) \times \sin^2\left(\frac{\Delta\lambda}{2}\right) \quad (19)$$

$$c = 2\arcsin(\min(1, \sqrt{a})) \quad (20)$$

$$\text{distance} = R \times c \quad (21)$$

Fig. 34: Haversine Formula

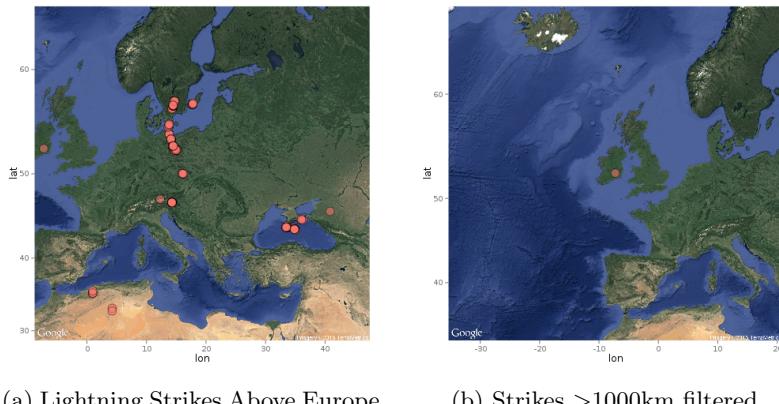


Fig. 35: Blitzortung data

Research Question 3

What SDR tools, processes and or algorithms need to be developed to identify instances of the three main DAM emission types detailed in Table. 1?

- Can existing tools and signal processing techniques be employed to find DAM emissions?
- What is required from an algorithm which might identify DAM emissions within an IQ signal?

Capturing DAM Emissions with the RTL2832 DAB SDR

The Radio Jupiter Pro tool was used to choose a date which was optimal for capturing DAM emissions. The Figure: 36a, was generated by taking a screen capture of the GQRX tool while connected to the HackRF SDR transceiver. The data was recorded at a bandwidth of 3MHz for an estimated 2 minutes. The multiple short wide bandwidth bursts are possibly instances of Jovian storm L-Bursts. This spectrogram is a very narrow window considering the capabilities of the HackRF device which has a maximum bandwidth of 20MHz. Unfortunately the HackRF is limited by the USB transfer speeds of the host computer, and the observations were recorded on a machine with USB 2.0, which prevented data being collected at larger bandwidths. Being limited to 2 minutes per screen capture is potentially of little value in hunting for DAM emissions, as Jovian storms may occur over several hours. Ideally a spectrogram plot generated from 24 hours worth of data is required.

Due to its recent release there is currently no tools available which are capable of interfacing with the HackRF SDR transceiver in order to generate a spectrogram plot from saved data. This speed limitation along with the lack of tooling, raised the possibility of using other devices. The first option being the RTL line of DAB TV receivers which are known to make reasonable SDR receivers, and have a wide selection of tooling already developed. The *rtl_power* utility is shipped with the firmware required to operate the SDR receiver and is capable of collecting power data over long periods of time with the view to generate spectrogram plots at a later point. One such tool is the *heatmap.py* utility which is designed to take the output from *rtl_power* and produce large

bandwidth long period spectrogram plots [Keen, 2015]. This was ideal for the purpose of hunting for DAM emissions.

The RTL based receivers have a similar operating range to the HackRF and align somewhat closely with the requirements to pick up DAM emissions from Jupiter [Hamradio-Science, 2012]. Table: 10 lists the operating ranges of both the HackRF and also the RTL DAB receiver. The RTL DAB receiver operates at 24MHz at the lower end of its operational range. This is still well within the 7MHz - 40MHz range of Jovian DAM emissions, but it is just outside the ideal range recommended by NASA's Radio Jove documentation of 20.1 MHz [NASA, 2012b]. The RTL device has a narrow maximum bandwidth of 2MHz, however this is potentially not such an issue, as rtl_power is designed to quickly retune the receiver and take a power reading to enable the sampling of large bandwidths. The retuning of the RTL receiver in order to take a power sample is not instant. It can take several seconds to take a single reading for a large bandwidth so this should be taken into account [Keen, 2015].

Device	Operating Range
HackRf	1MHz - 6GHz
RTL2832U/R820T	24MHz - 1850MHz
SDRT	18MHz - 40MHz

Table 10: RTL vs HackRF and SDRT Requirements

Methodology

The following methodology was followed during this experiment:

1. RTL2832U/R820T Dongle connected to the 21MHz Dual Dipole Array
2. rtl_power was left running for 24 hours at a time recording data
3. A spectrogram was generated using the heatmap.py utility from data collected in the previous 24 hours

The plots shown in Figures: 36 and Figures: 37 show possible instances of DAM emissions captured using the RTL receiver over extended recording sessions of 24 hours. In Figures: 36c and 36d, it is possible to see the interference from amateur radio signals while Figures: 37 also show the extra noise and interference

generated by the Sun when it is above the horizon and crosses into the antenna beam. Using both the `rtl_power` and `heatmap.py` utilities, it seems feasible to capture DAM emissions on a spectrogram.

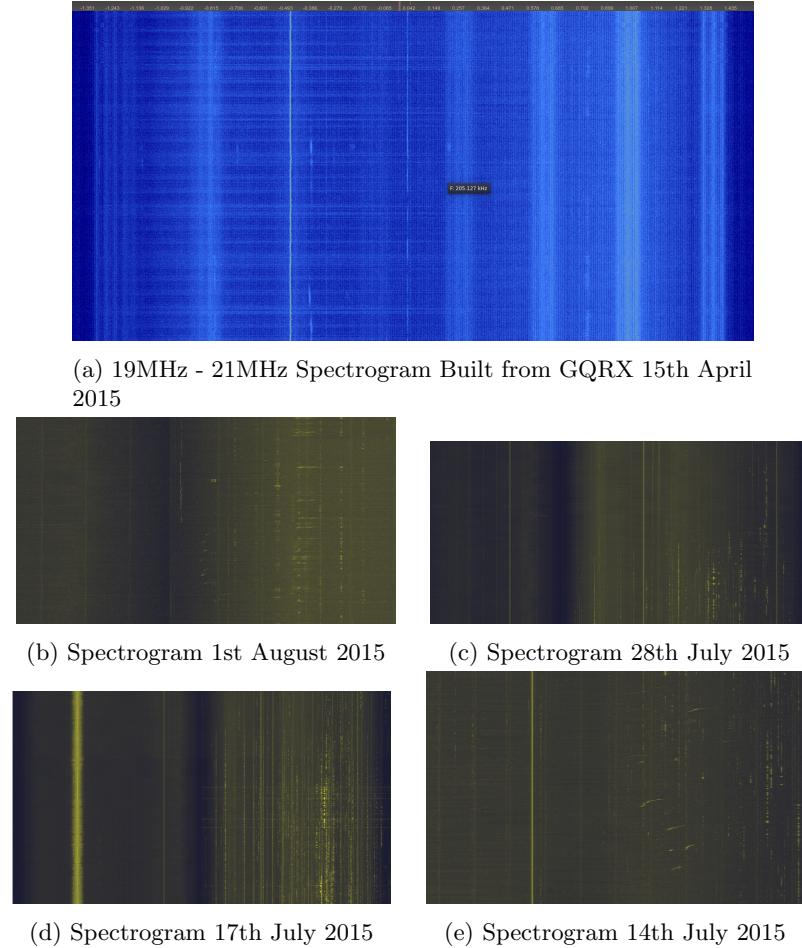
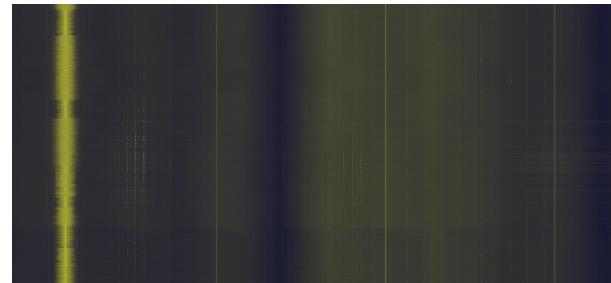
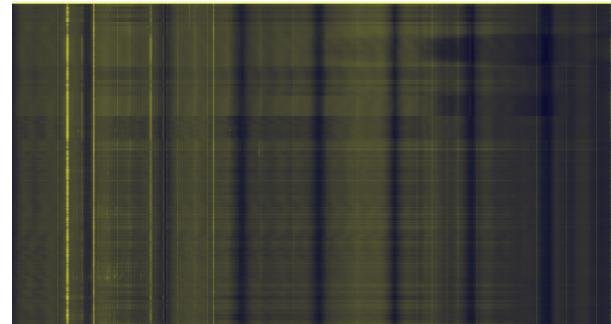


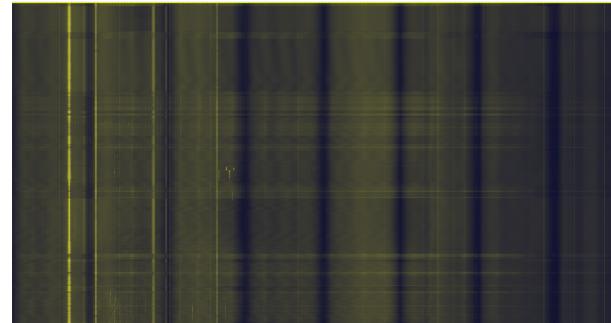
Fig. 36: 24MHz - 28MHz Spectrograms of `rtl_power` data plotted using `heatmap.py`



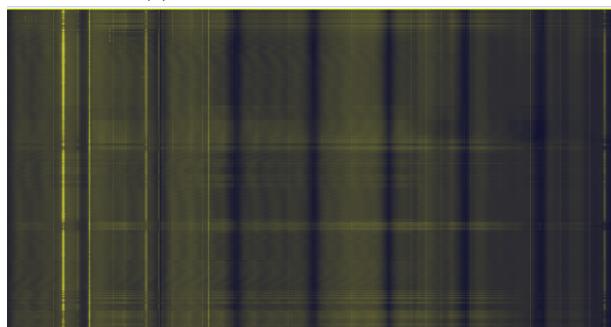
(a) Spectrogram 10th July 2015



(b) Spectrogram 25th June 2015



(c) Spectrogram 24th June 2015



(d) Spectrogram 23rd June 2015

Fig. 37: 24MHz - 40MHz Spectrograms of rtl_power data plotted using heatmap.py

Implementing a HackRF Compatible Flow-Graph in GNURadio

As mentioned previously there is currently no existing tool which is capable of generating spectrogram plots using a HackRF transceiver from previously saved data. In order to rectify this, the methods of generating spectrograms was investigated. One method requires that the digital signal is broken up into chunks of the original bandwidth, and measured using a total power meter. It is not possible to measure the power at an individual frequency, a band of frequencies must be measured instead [Keen, 2015].

Figures: 16 and 48 shows how a signal is stored digitally once sampled as an I/Q plot. Each data point stored contains the in phase component and the quadrature phase component. The equation shown in Figure: 38 can be used in order to calculate the total noise power from such a I/Q digital sample [Nelson, 2015].

$$\text{Power} = I^2 + Q^2 \quad (22)$$

Fig. 38: Converting in-phase and quadrature-phase to power values

The equation listed in Figure: 38 has been implemented in within a GNURadio flow-graph and contains a software implementation of a total power radiometer [Nelson, 2015]. The functionality of a radiometer or total power meter provides the means to measure a chunk of bandwidth from a sample and produce a total noise power value which can then be plotted or used elsewhere within a larger GNURadio flow-graph.

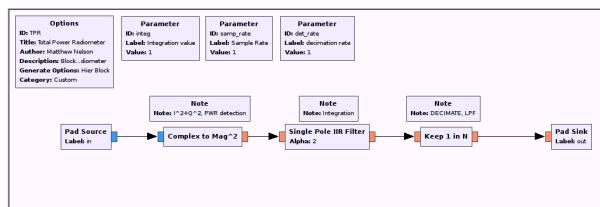


Fig. 39: Total Power Meter Implemented in GNURadio [Nelson, 2015]

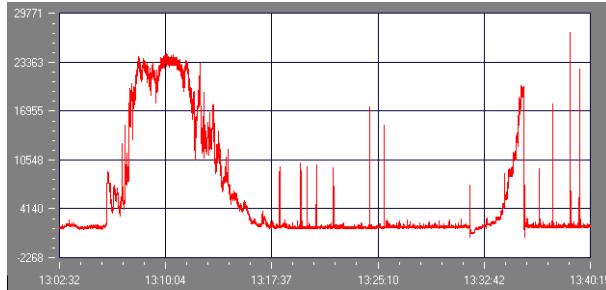


Fig. 40: Radio Skypipe Software Power Plot [Radio-Sky-Publishing, 2015]

Methodology

The following methodology was followed during this experiment:

1. Design a GNURadio flow-graph prototype to generate a set of test signals
2. Design a GNURadio flow-graph prototype to which filters a signal using a bandpass filter
3. Design a GNURadio flow-graph which incorporates the total power meter in order to produce a power plot

The Figure: 40 shows a voltage power graph generated using the Radio Skypipe software Radio-Sky-Publishing [2015]. Such a graph can be produced by measuring the power from a band of frequency and plotting the values against time. A prototype GNURadio flow-graph (Figure: 43a) was designed which generates a test signal as seen in Figure: 43b. This signal was then passed through a bandpass filter, which removes signals outside the permitted frequency range, the result of which can be seen in Figure: 43c.

This flow-graph provided the means to isolate and measure the power for individual bands of frequency while ignoring frequencies outside this range. This flow-graph (Figure: 43e) was then upgraded to incorporate the total power meter as seen in Figure: 43d. It is possible to capture live power data within a frequency band directly from a osmocom source such as the HackRF, or alternatively from previously recorded data.

A power graph was generated from I/Q data collected during the 20th March 2015 for the solar eclipse radio propagation experiment. The plot shows the signal power (V) rise as the eclipse reaches max totality and can be seen in Figure: 43f, which compliments the previously generated signal power (dB) plot shown in Figure: 26.

Radiometers can be used to produce signal intensity plots and thereby detect natural radio emissions such as the Jovian DAM emissions, cosmic microwave background and other discrete astronomical sources such as galaxies [Condon and M., 2010]. In order to make use of a radiometer attached to the telescope for radio astronomical applications it must first be calibrated. Nelson [2015] suggested the use of 3 sources with known temperatures such as liquid nitrogen, ice water and hot water as demonstrated in Figure: 41 in order to calibrate the radiometer.

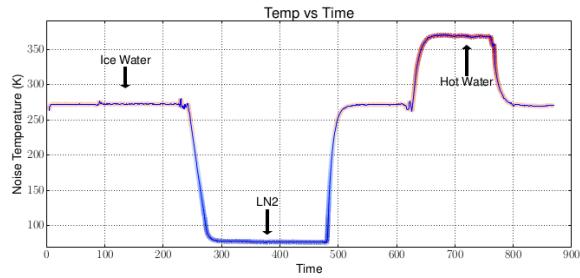


Fig. 41: Graph of calibrated noise temperature [Nelson, 2015]

$$k \approx 1.38 \times 10^{-23} Joule K^{-1} \quad (23)$$

$$T_N \equiv \frac{P_v}{k} \quad (24)$$

Fig. 42: Converting Power(V) to Temperature(K)

In the formula contained in Figure: 42, k is the Boltzmann constant and T_N is the noise temperature. Using this formula it is possible to calculate the noise temperature value (K) for a noise source power value (V) [Condon and M., 2010].

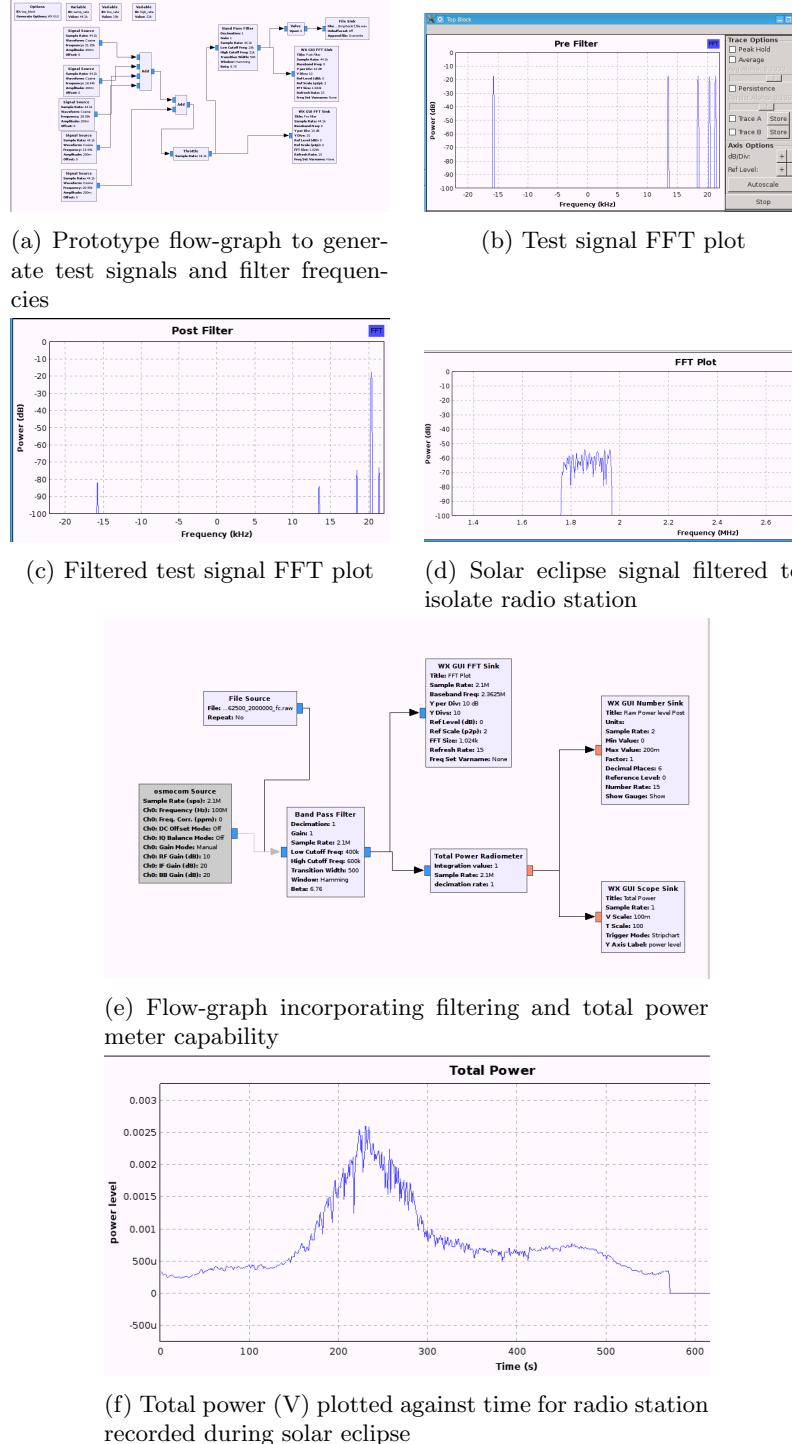


Fig. 43: GNURadio flow-graphs to generate total power plots from saved data

Conclusions

This thesis presented a contribution to the areas of software defined radio and amateur radio astronomy. The hypothesis of this thesis is that it is possible to design and construct a low cost radio telescope which is capable of capturing Jovian storm emissions in the DAM range. The chosen antenna design is based on the NASA Radio Jove project while a software defined radio receiver such as the HackRF or RTL DAB system is used in place of the custom hardware offered in the Radio Jove kit. This hypothesis lead to the development of a suite of open source tools and resources which an amateur radio astronomer on a budget might utilise.

Chapter 2 discussed the radio antenna build and the special resources required in order to perform a site suitability survey. An opportunity to be involved in a public radio propagation experiment during the March 2015 solar eclipse aided in the verification of the software defined radio receiver, while the antenna was verified by capturing potential instances of DAM emissions were recorded during an optimal observation period.

A process for determining the electrical power requirements of an off grid listening site was discussed in Chapter 3. Appropriate capacity sizing to provide adequate power to run the listening site for extended periods using solar renewable solution to charge batteries was also discussed. The computational and networking requirements were also determined for a system capable of performing the necessary functions of a radio telescope listening station.

In Chapter 4, the system for flagging occurrences of amateur radio transmissions was developed, it made use of the global DXCluster systems which the amateur radio enthusiast community use to share information regarding transmissions which were observed. A system for flagging occurrences of natural interference from lightning strikes was also developed. The system makes use of data gathered from the Blitzortung global lightning detection system.

Chapter 5 presented the process of generating spectrograms from data recorded using the RTL DAB receiver. Spectrograms provide the means to visualise large portions of the radio spectrum over long periods, in the hope of identifying periods of Jovian storm activity in the DAM range. A GNURadio flow-graph was developed in order to generate power plots using a radiometer implemented in

SDR. Radiometers are used to measure the signal intensity of radio emissions and are a standard tool in the radio astronomer toolbox.

Thesis Appraisal

In the initial proposal I conjectured at the potential pitfalls which would befall the thesis and hinder progress. I was not prepared however for the inane problems which ultimately caused the most trouble. Examples include the laptop USB ports being too slow to operate the HackRF at higher bandwidths. This forced the sampling of much narrower bandwidths which made it very difficult to spot DAM emissions as they often are bigger than the window of the radio spectrum. A second troublesome issue encountered was the antenna mounting poles being too large to transport by car. To address this it was necessary to reduce size of the poles by 25%. This reduced the potential configurations for which the telescope could be set to 10 ft, and 15 ft. This resulted in wasted observation opportunities as Jupiter was at a point in the sky where it was not possible to aim the telescope at.

Nor was I prepared for the complexity of digital signal processing and machine learning. I have taken mathematics refresher courses in order to understand the fundamentals of working with these signals. Several times, I made presumptions that I understood a concept only to discover it was far more complex which then added almost unbounded risk to the project. Due to issues encountered such as these, the scope has been changed drastically. I no longer expect to produce an automated identification algorithm to spot DAM emissions in recorded data. I expect an implementation might instead be completed in future work.

I am delighted to say I have lost no enthusiasm for the topic, after my experiences I am in fact encouraged to continue working on the topic further. I am considering applying to a doctoral program and hope pursue a research career in Astronomy.

Future Work

A dissertation is a work of scholarly investigation that is grounded in the research literature and differs from a report or a book. It is judged on a prescribed set of academic criteria. Although the likely outcomes are tentative at the start of the program, it is useful to incorporate them into the research proposal to help focus the work program.

It is envisioned the time and frequency values associated with this data related to human signals, along with the data gathered regarding lightning strikes could be used to generate an overlay for a waterfall spectrogram diagram of the previous 24 hours worth of data collected by the telescope.

Blitzortung client needs to be fleshed out further, however

It was not feasible to produce a system as complex as rtl-power within the scope of this dissertation, however it might be possible to replicate

Once calibration is complete it would then be possible to take accurate readings for signal intensity using the SDRT system [Condon and M., 2010].

Appendix

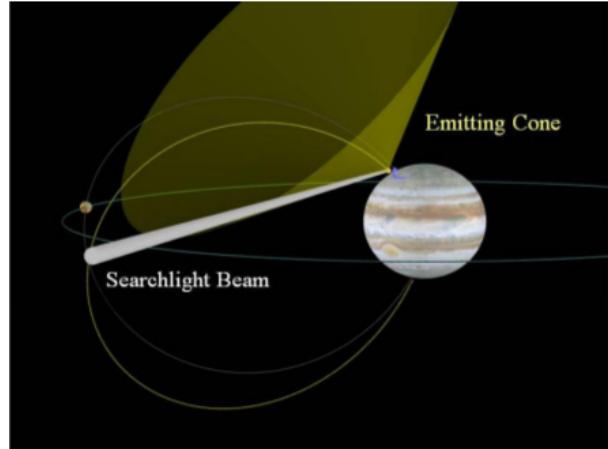


Fig. 44: A searchlight beam model of Jupiter's decametric radio emissions [Imai et al., 2008]

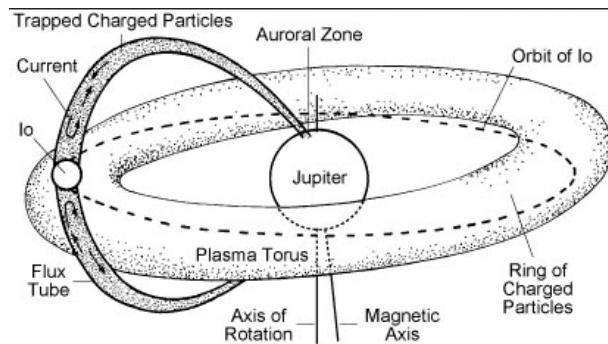
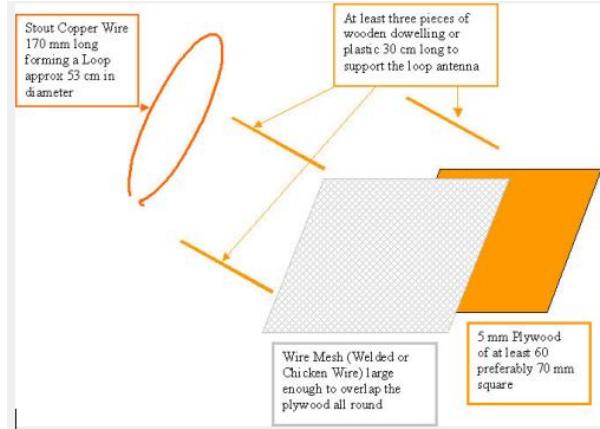


Fig. 45: Io Flux Tube and the Plasma Torus [Lang, 2010]



(a) 21 MHz Shortwave Loop Antenna Radio Telescope Design [Greef, 2012]



(b) 21 MHz Shortwave Loop Antenna Radio Telescope Design [Greef, 2012]

(c) 21 MHz Shortwave Loop Antenna Radio Telescope Design [Greef, 2012]

Fig. 46: 21MHz Shortwave Loop Design

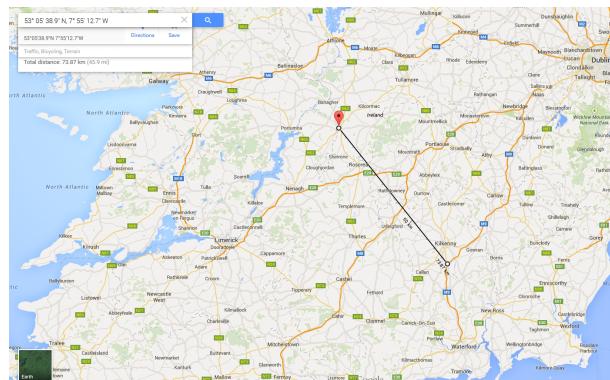
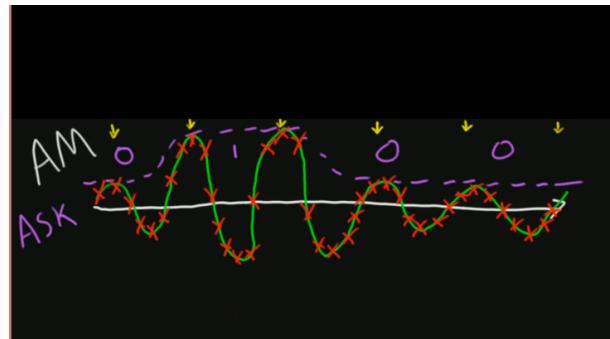
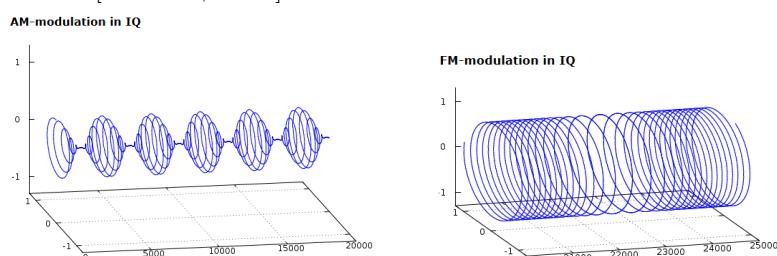


Fig. 47: Distance between the Birr and Kilkenny site survey



(a) Sampling an Analogue Amplitude Modulation Signal
[Ossmann, 2015c]



(b) I/Q Sample Polar Plot of an AM Modulated Signal [Kuisma, 2014]

(c) I/Q Sample Polar Plot of an FM Modulated Signal [Kuisma, 2014]

Fig. 48: Signal Modulation

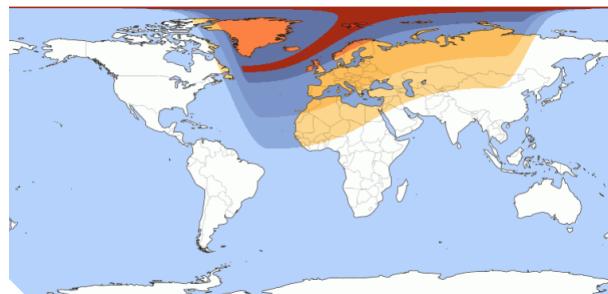


Fig. 49: Partial Solar Eclipse 20th March 2015 [timeanddate.com, 2015]

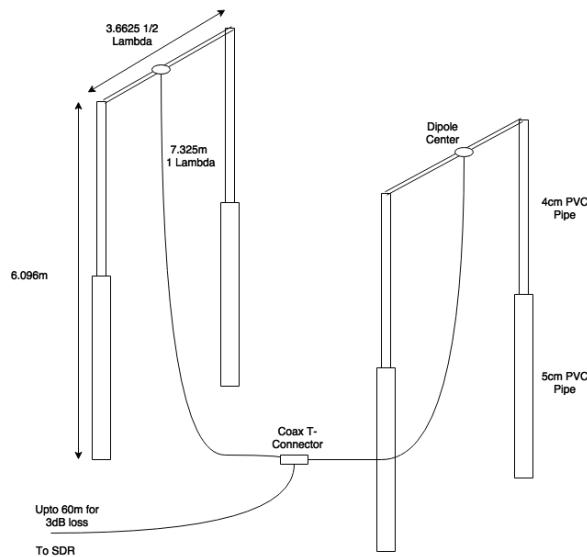


Fig. 50: SDRT Dual Dipole Antenna Design based on NASA RadioJove

Bibliography

- ARRL. *ARRL Operating Manual 7th Edition*, 2000. URL <http://www.arrl.org/shop/ARRL-Operating-Manual-10th-Edition/>.
- Thomas Ashcraft. Jupiter 27 september 2013 n event, September 2013. URL http://www.heliotown.com/Jupiter_Sep272013_N_Event.html.
- John W. Belcher. The jupiter-io connection: An alfvén engine in space. *Science*, 238(Oct 9):170–176, 1987.
- S. K. Bose, S. Sarkar, and A. B. Bhattacharyya. Jovian decametric radio emission: An overview of the planetary radio astronomical observations. *Indian Journal of Radio and Space Physics*, 37:77–108, 2008.
- Michael Bryce. *Emergency Power for Radio Communications*, chapter 3, page 12. ARRL - The national association for amateur radio, 2011. ISBN 978-0-87259-615-3. URL <http://www.arrl.org>.
- F.B. Burke and L. K. Franklin. Obervations of variable radio source associated with the planet jupiter. *Journal of Geophysical Research*, 60(213), 1955.
- Comreg. *Overview Comreg - Radio Spectrum*. Commission for Communications Regulation, 2014. URL http://www.comreg.ie/radio_spectrum/overview.496.html.
- J.J. Condon and Ransom S. M. Essential radio astronomy - radiometers, 2010. URL <http://www.cv.nrao.edu/course/astr534/Radiometers.html>.
- ECA&D. European climate assessment and dataset, 2015. URL <http://eca.knmi.nl/dailydata/customquery.php>.
- J. M. Freidt. Gnuradio as a digital signal processing environment: Application to acoustic wireless sensor measurement and time and frequency analysis of periodic signals. *Joint UFFC EFTF and PFM Symposium*, pages 278–281, 2013.
- Gnuradio. Tutorials - gnuradio, 2014. URL <http://gnuradio.org/redmine/projects/gnuradio/wiki/Tutorials>.
- B. Greef. A simple decametric radio telescope for jupiter, 2012. URL http://www.ukaranet.org.uk/uk_amateurs/bobgreef/.
- Hamradio-Science. Rtl2832u / r820t vs rtl2832u / e4000, 2012. URL <http://www.hamradioscience.com/rtl2832u-r820t-vs-rtl2832u-e4000/>.
- K. Imai, L. Garcia, F. Reyes, M. Imai, J. R. Thieman, and M. Ikuta. A Search-light Beam Model of Jupiter’s Decametric Radio Emissions. *AGU Fall Meeting Abstracts*, page B1673, December 2008.

- Kyle Keen. Great-circle distance calculations in r, 2015. URL <https://github.com/keenerd/rtl-sdr-misc>.
- M. G. Kivelson, K. K. Khurana, R. J. Walker, C. T. Russell, J. A. Linker, D. J. Southwood, and C. Polanskey. A magnetic signature at io: Initial report from the galileo magnetometer. *Science*, 273, July 1996.
- Dirk Koopman. Dxspider, 2007. URL <http://www.dxcluster.org/main/>.
- Mikael Q Kuisma. *I/Q Data for Dummies*, 2014. URL <http://whiteboard.ping.se/SDR/IQ>. Complex Numbers in DSP.
- K. R. Lang. Io flux tube and plasma torus, 2010. URL http://ase.tufts.edu/cosmos/view_picture.asp?id=1174.
- J Litva and B.J. Rook. *Beverage Antennas for HF Communications, Direction Finding and Over-the-horizon Radars*, chapter 1, pages 1–3. Communications Research Centre, 1976. URL <http://www.nrccdxas.org/articles/BevAnt0876.pdf>.
- Joe McCauley. Craf the esf expert committee on radio astronomy frequencies, 2013. URL http://www.craf.eu/newsletters/newsletter27_0713.pdf.
- MET. Download historical climate data for our synoptic stations, 2015. URL <http://www.met.ie/climate-request/>.
- NASA. *The Effects of Earth's Upper Atmosphere on Radio Signals*, 2012a. URL <http://radiojove.gsfc.nasa.gov/education/educ/radio/tran-rec/exerc/iono.htm>.
- NASA. *Antenna Kit and Manual Developed for NASA Radio JOVE Project by The Radio JOVE Project Team*, 2012b. URL http://radiojove.gsfc.nasa.gov/telescope/ant_manual.pdf.
- Matthew-Erik Nelson. Implementation of a total power radiometer in software defined radios, 2015. URL <https://github.com/matgyver/Radiometer-SDR-Thesis>.
- Steve Nichols. Partial solar eclipse propagation experiment, march 20th 2015, 2015a. URL <http://forums.thersgb.org/index.php?threads/partial-solar-eclipse-propagation-experiment-march-20th-2015.125/>.
- Steve Nichols. Partial solar eclipse propagation experiment, march 20th 2015, 2015b. URL <http://www.g0kya.blogspot.ie/2015/02/partial-solar-eclipse-propagation.html>.
- Michael Ossmann. *Software Defined Radio with HackRF*, 2015a. URL <http://greatscottgadgets.com/sdr/>.

- Michael Ossmann. *Software Defined Radio with HackRF*, 2015b. URL <http://greatscottgadgets.com/sdr/9>. Aliasing.
- Michael Ossmann. *Software Defined Radio with HackRF*, 2015c. URL <http://greatscottgadgets.com/sdr/7>. Complex Numbers in DSP.
- Michael Ossmann. *Software Defined Radio with HackRF*, 2015d. URL <http://greatscottgadgets.com/hackrf/>. HackRF One.
- Mario Pineda-Krueh. Great-circle distance calculations in r, 2010. URL <http://www.r-bloggers.com/great-circle-distance-calculations-in-r/>.
- Radio-Sky-Publishing. *Radio Jupiter Pro*, 2014. URL <http://www.radiosky.com/rjpro3ishere.html>.
- Radio-Sky-Publishing. *Radio Skypipe Pro*, 2015. URL <http://www.radiosky.com/skypipeishere.html>.
- RSGB. *RSGB Radio Communication Handbook*, 2014. URL http://www.rsgbshop.org/acatalog/Online_Catalogue_Technical_6.html.
- Steven W. Smith. *Digital Signal Processing A Practical Guide for Engineers and Scientists*, chapter 1, pages 1–3. Newnes, 2003a. ISBN 0-75067444-X. What is DSP.
- Steven W. Smith. *Digital Signal Processing A Practical Guide for Engineers and Scientists*, chapter 3, pages 39–44. Newnes, 2003b. ISBN 0-75067444-X. Sampling Theorem.
- Superkuh. Radio spectrum, 2007. URL http://superkuh.com/radio/2014-08-26_17-55_70-1000_25k/.
- timeanddate.com. Total solar eclipse - kilkenny, ireland, 2015. URL <http://www.timeanddate.com/eclipse/in/ireland/kilkenny?iso=20150320>.
- E. Wanke, R. Andersen, and T. Volgnandt. *A WorldWide Low Cost Community Based Time of Arrival Lightning Detection and Lightning Location Network*, 2014. URL http://www.blitzortung.org/Documents/TOA\Blitzortung_RED.pdf.
- M. Wilkinson and J. Kennewell. A project to detect radio emissions from jupiter. *Southern Sky*, 1994. URL <http://www.spaceacademy.net.au/spacelab/projects/jovrad/jovrad.htm4>.