Observing Jovian Decametric Radio Emissions with a Software Defined Radio Telescope Interim Report

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Glossary

DAM decameter radio emissions in the 10-100M wavelengths. 5–14, 16, 17, 22, 23, 31

HF High Frequency. 7

IFT Io Flux Tube is a cylindrical area of space containing magnetic field lines. 6, 17

IOT Internet of Things a buzzword for everything connecting to everything. 14, 16, 29

IPT Io Plasma Torus is created by ionizing neutral atmospheric gas such as sulphur. 5

IQ Imaginary Quadrature signal - Complex signal data and quadrature phase values in a digital signal sample. 16, 31

LOFAR Low Frequency Array - https://www.astron.nl/lofar-telescope/lofar-telescope. 26

preamp preamplifier - is an electronic amplifier that prepares a small electrical signal for further amplification or processing. 25

RF Radio Frequency. 25

MW MW - Medium Wave frequencies usually in the wavelengths 300 kHz - 3 MHz. 27

RSGB RSGB - The Radio Society of Great Britain. 27

SDR Software Defined Radio is the creation of radio functions within software rather than as previously using hardware. 11, 13–16, 19, 22, 25, 31, 34

SWR Standing Wave Ratio is the ratio of impedance between receiver and antenna. 23, 24

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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].

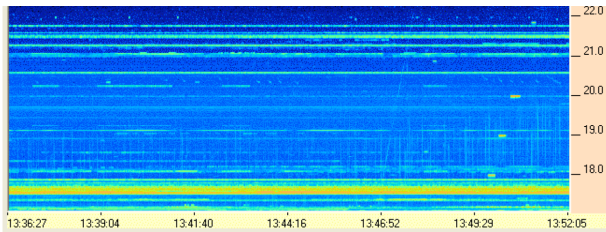

Fig. 1: Decametric Radio Emissions [Ashcraft, 2013]

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 corotation 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,

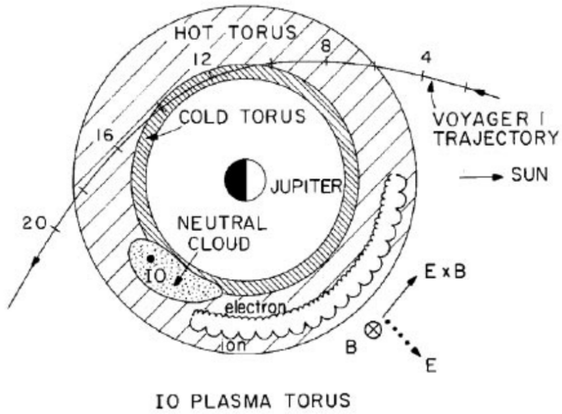

Fig. 2: Neutral Gasses in Orbit of Io [Belcher, 1987]

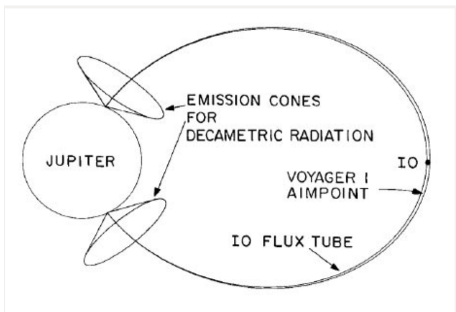

Fig. 3: Magnetic Flux Tube linking Jupiter and its satellite Io [Belcher, 1987]

1987]. Figures 3 and 25 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].

As Io orbits within this flux torus it acts as a unipolar conductor [Bose et al., 2008], and Alfvén waves are regularly produced which carry an electric charge along the magnetic field lines between Io and Jupiter [Bose et al., 2008].

These Alfvén waves reflect between Jupiter's ionosphere at both north and south poles and Io upto 9 times [Bose et al., 2008] while following Io through its orbit, thereby acting as a standing wave [Bose et al., 2008]. 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.

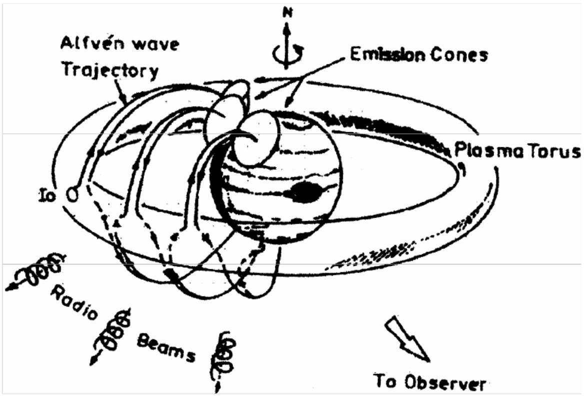

Fig. 4: Alfvén Waves following Io through its orbit and the DAM Emission cones [Bose et al., 2008]

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 range significantly. Despite these obstacles, there are sections of the HF spectrum

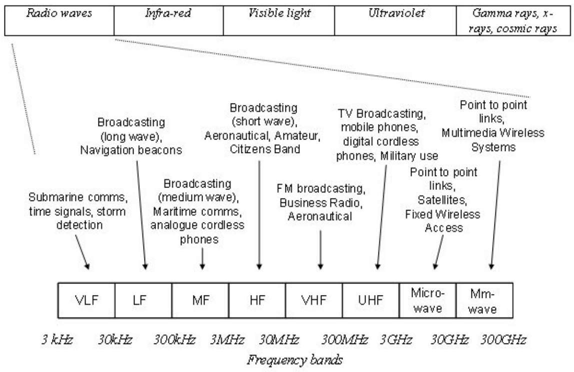

Fig. 5: Irish Regulatory Transmission Ranges [Comreg, 2014]

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.

$$\lambda = \frac{c}{f} \tag{1}$$

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

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 fig 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.

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

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

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

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

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 $1 - 10x10^{-3}s$ long while L-Bursts can be *0.5-5s* in length.

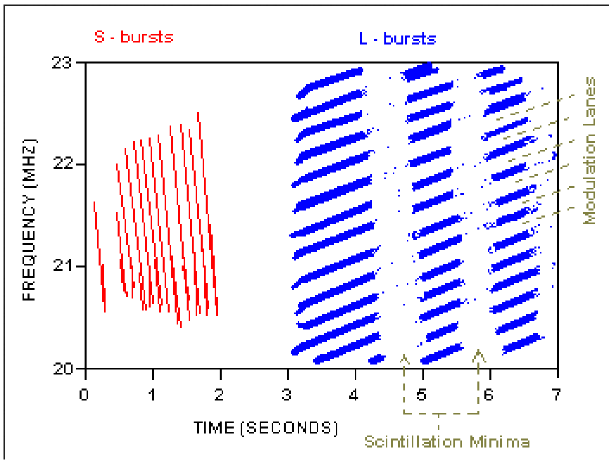

Fig. 9: Ideal DAM Emissions types from Jupiter [Wilkinson and Kennewell, 1994]

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.

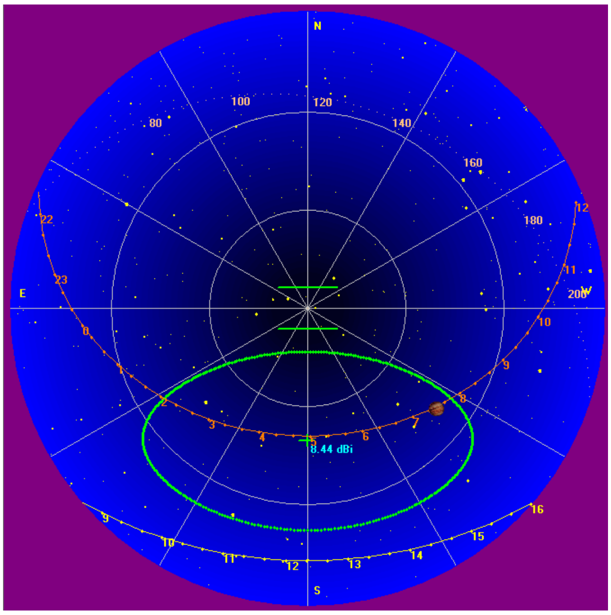

Fig. 10: Dual Dipole Antenna Beam at 20FT and 135deg phasing South [NASA, 2012b]

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 or so 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.

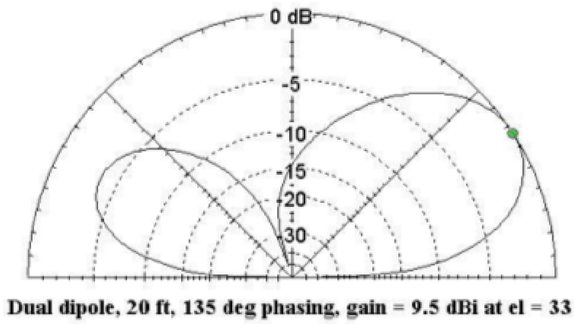

Fig. 11: Dual Dipole Antenna Array Beam[NASA, 2012b]

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.

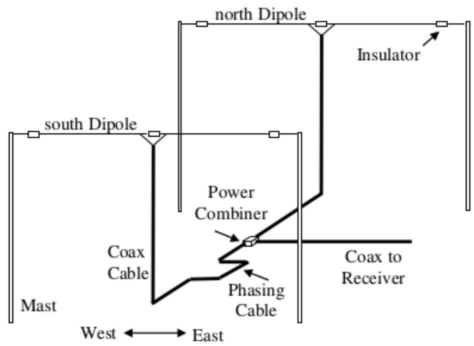

Fig. 12: Dual Dipole Antenna Array [NASA, 2012b]

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.

- create listening schedule during which DAM emissions are likely to occur
- develop SDR prototype mechanism for gathering raw data from the antenna
- develop software scheduling system which to activate the collection of data from the antenna remotely

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 dxspider server 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 toolkit [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 feasible to use wireless technologies such as Zigbee, WIFI or Bluetooth to stream collected data to a central facility?
   - If wireless technologies prove too slow, is 10/100/1000 MBit Ethernet suitable instead? Or link aggregation technologies such as EtherChannel or LACP.
   - Can a low powered computing platform such as the Raspberry Pi 2B or Beaglebone Black be used to host the system, or will a more powerful system be required?
2. *What processes or algorithms need to be developed to filter or flag known instances of human radio 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 processes and algorithms need to be developed to identify instances of the three main DAM emission types detailed in Table. 1?*
   - Can existing signal demodulation 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. 24.

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. 26, 27 and 28.

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.

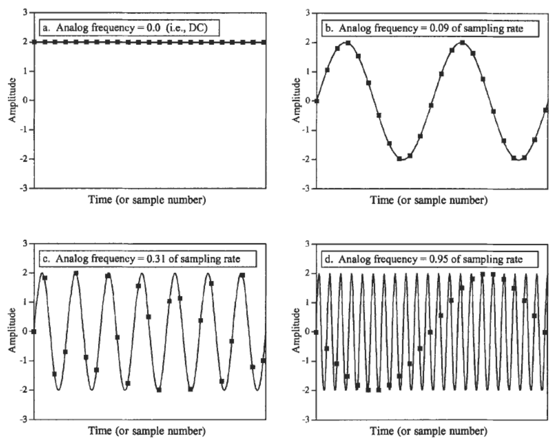

Fig. 14: Sampling an Analogue Signal [Smith, 2003b]

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].

$$f_s > 2f \tag{6}$$

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 GNURadio 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].

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: 32 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 the point on the imaginary axis Figure: 16 shows how these I/Q values are plotted periodically [Kuisma, 2014].

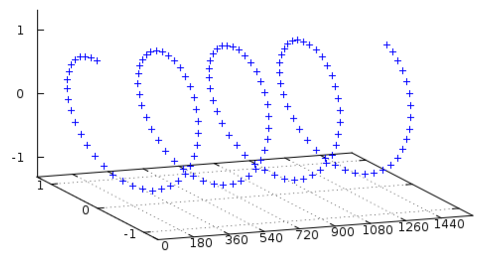

Fig. 16: I/Q Samples Helix [Kuisma, 2014]

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

Main Milestones Anticipated

The following Table. 3 details the milestones which have been identified and agreed to date. It has been updated for the Interim Report to include completed milestones and those in progress:

Deadline	Start	End	Summary
Antenna Build	October 14	March 15	Settle on a design for the telescope, source the parts for the build and finally construct the prototype antenna which will act as a template for the second dipole.
Site Survey	March 15	March 15	Perform a site survey using a spectrum analyser connected to the prototype antenna.
Deploy Dual Dipole Antenna	March 15	March 15	Deploy the antenna array at a suitable location and begin to collect data for analysis.
Interim Report	January 15	(Hard Deadline) 30th April 15	Poster presentation to review panel and supervisor on 19th May
Data Collection	March 15	July 15	Once the antenna is deployed begin collecting data for analysis.
Data Analysis and System Development	March 15	July 15	Develop analytical SDR tools to filter or flag interference. Develop algorithms to detect the various DAM emission.
Evaluate IOT Technologies	January 15	July 15	Experiment with the various IOT technologies which could potentially be used to create a self sufficient listening array.
Final Report Submission	June 15	(Hard Deadline) September 15	First draft to supervisor due in early June 15. Complete draft due 24th August. Final submission 4th September

Table 3: Milestones Anticipated

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 impedance between the receiver and the antenna. The use of a SWR analyser becomes invaluable in this process.

Fig. 17: 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 center. 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: 17.

The SWR equations shown in Figure: 18 is the equations where $|\rho|$ 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].

$$SWR = \frac{1 + |\rho|}{1 - |\rho|} \tag{7}$$

$$|\rho| = \frac{SWR - 1}{SWR + 1} \tag{8}$$

$$|\rho| = \sqrt{\frac{P_r}{P_f}} \tag{9}$$

Fig. 18: Standing Wave Ratio Equations

$$|\rho| = \frac{1.2 - 1}{1.2 + 1} \tag{10}$$

$$|\rho| = 0.09090909090909088 \tag{11}$$

$$0.09090909090909088 = \sqrt{\frac{P_r}{100}} \tag{12}$$

$$0.09090909090909088^2 = \frac{P_r}{100} \tag{13}$$

$$P_r = 0.826446280991735 \tag{14}$$

Fig. 19: 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: 19 of 0.826446280991735 which is a loss of 17.35% or about 1dB which is considered reasonable [ARRL, 2000].

Table: 4 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
6 × PL259	12.00
2 × SO239	4.00
SMA-SO239 Adapter	4.50
T Adapter	3.00
Patch Lead	5.00
2 × 4m 5cm Pipe	15.00
2 × 4m 4cm Pipe	15.00
Total	123.50

Table 4: Antenna Build Cost

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: 20. 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: 21. 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 preamplifier (preamp) in order to boost the gain on the input signal.

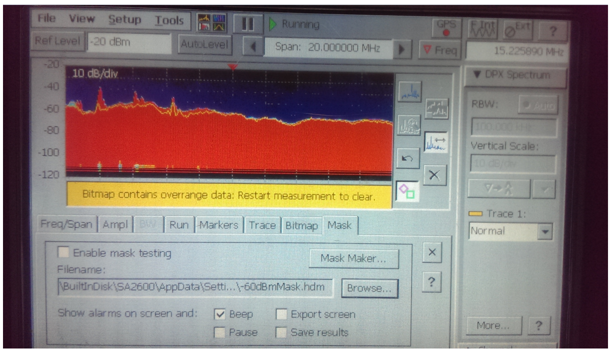

Fig. 20: Site Survey performed using a Tektronics SA2600 Spectrum Analyser

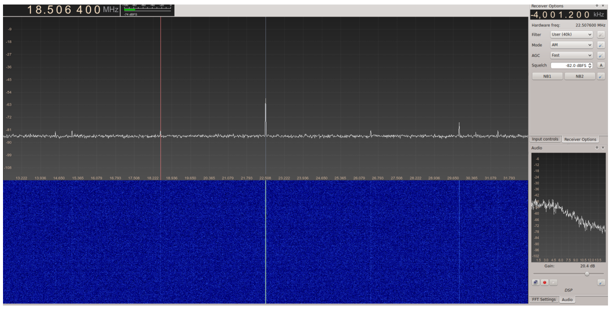

Fig. 21: Site Survey performed using HackRF One

In May 2013, the Solar Physics Group from Trinity College Dublin, performed a site survey at Birr Castle to assertain 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: 22. The report concluded that the 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: 5 details the results collected at the Kilkenny site and also 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.

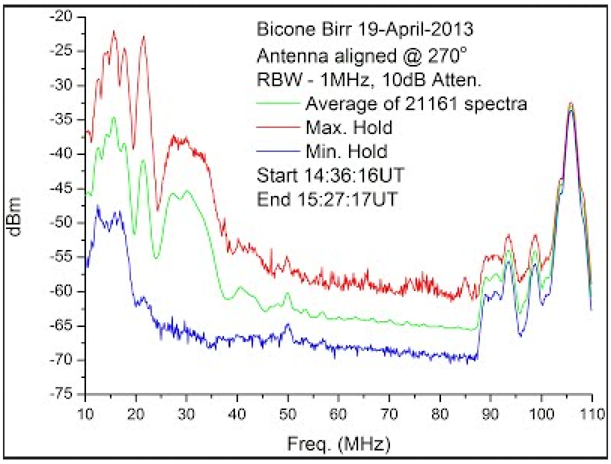

Fig. 22: LOFAR Site Suitability Survey performed at Birr Castle [McCauley, 2013]

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 5: 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 [2015] of the Radio Society of Great Britain (RSGB).

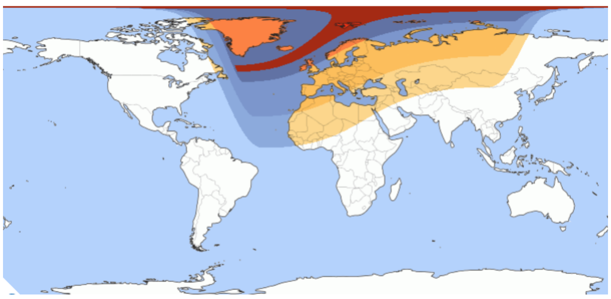

Fig. 23: Partial Solar Eclipse 20th March 2015

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 feasible to use wireless technologies such as Zigbee, WIFI or Bluetooth to stream collected data to a central facility?
- If wireless technologies prove too slow, is 10/100/1000 MBit Ethernet suitable instead? Or link aggregation technologies such as EtherChannel or LACP.
- Can a low powered computing platform such as the Raspberry Pi 2B or Beaglebone Black be used to host the system, or will a more powerful system be required?

Research Question 2

What processes or algorithms need to be developed to filter or flag known instances of human radio 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.

Research Question 3

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

– Can existing signal demodulation techniques be employed to find DAM emissions?
– What is required from an algorithm which might identify DAM emissions within an IQ signal?

Software 1

Conclusions

TODO Write me.

- sum up the answers to all the questions
- state contributions again
- where my work fits in the grander scheme
- further work

$\mathcal{O}(n \log n)$
[Eaton et al., 2009] [RSGB, 2014]

Contribution to Research Knowledge Anticipated

The contributions to research knowledge which are anticipated are listed as follows:

1. A low cost and scalable radio telescope listening platform design which Amateur astronomers can use to collaborate on radio astronomical research.
2. A rudimentary SDR solution to filter or flag human and natural radio interference from observations.
3. An SDR solution to flag possible Jovian or Solar radio emissions such as those listed in Table. 1.

Appendix

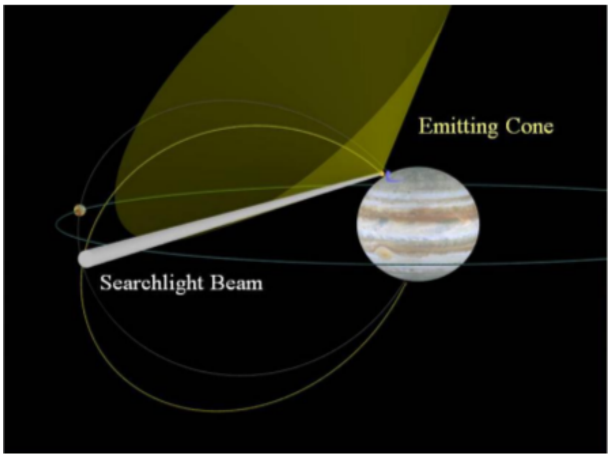

Fig. 24: A searchlight beam model of Jupiter's decametric radio emissions [Imai et al., 2008]

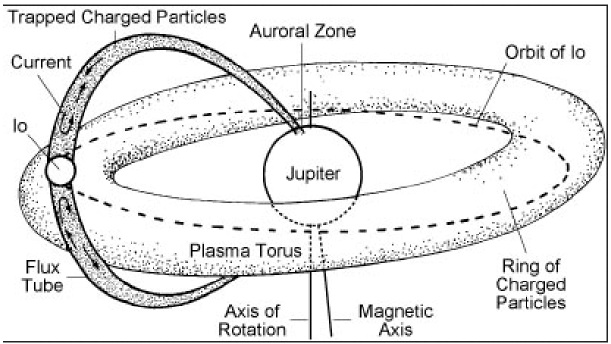

Fig. 25: Io Flux Tube and the Plasma Torus [Lang, 2010]

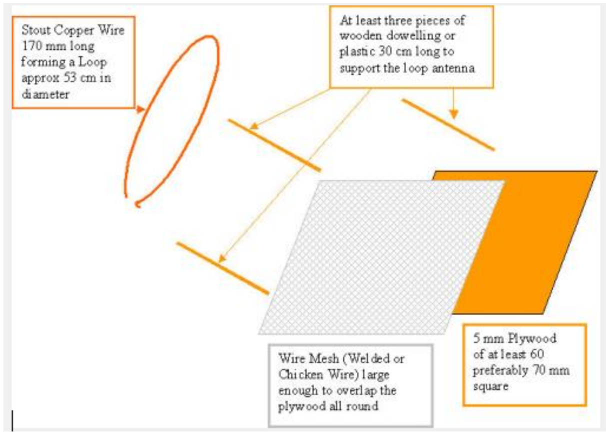

Fig. 26: 21 MHz Shortwave Loop Antenna Radio Telescope Design [Greef, 2012]

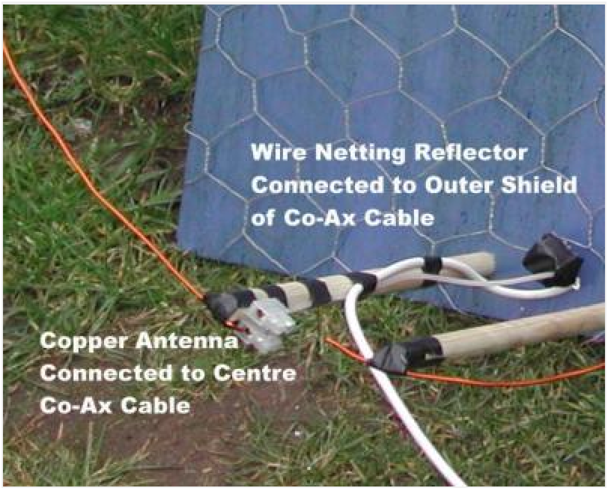

Fig. 27: 21 MHz Shortwave Loop Antenna Radio Telescope Design [Greef, 2012]

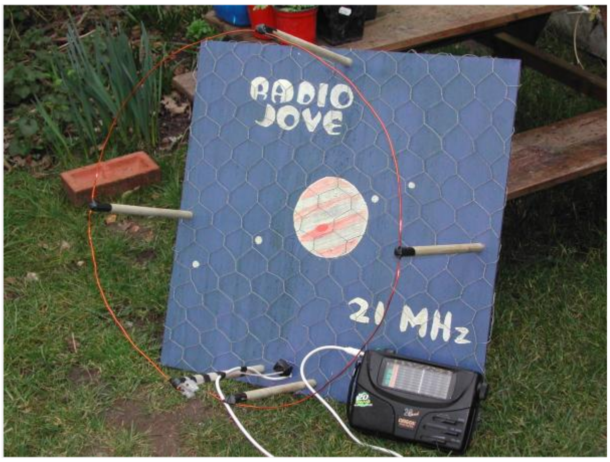

Fig. 28: 21 MHz Shortwave Loop Antenna Radio Telescope Design [Greef, 2012]

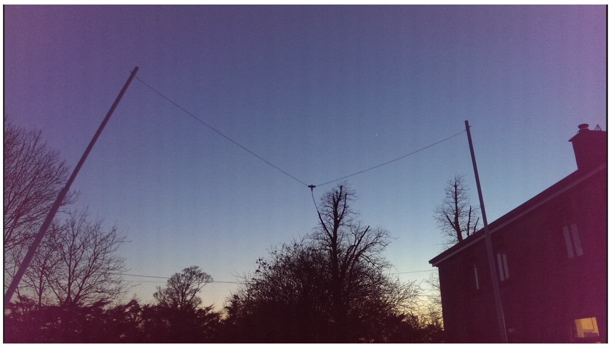

Fig. 29: Dual Dipole Antenna Deployment

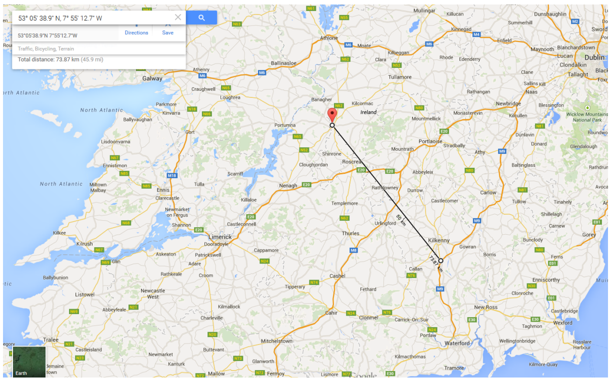

Fig. 30: Distance between the Birr and Kilkenny site survey

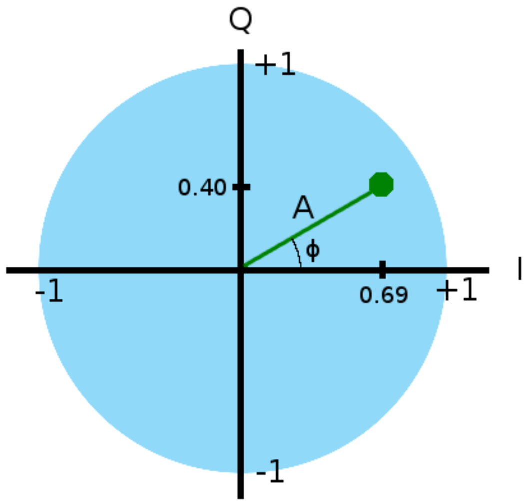

Fig. 31: I/Q Samples Polar Plot [Kuisma, 2014]

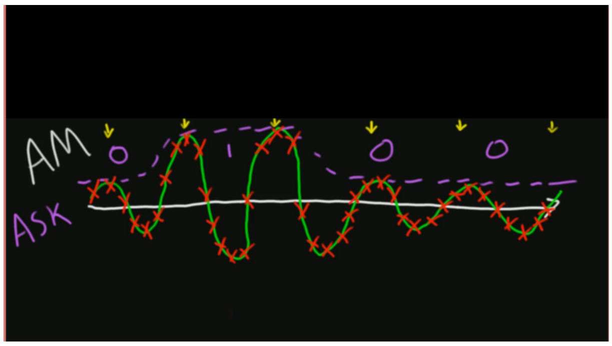

Fig. 32: Sampling an Analogue Amplitude Modulation Signal [Ossmann, 2015c]

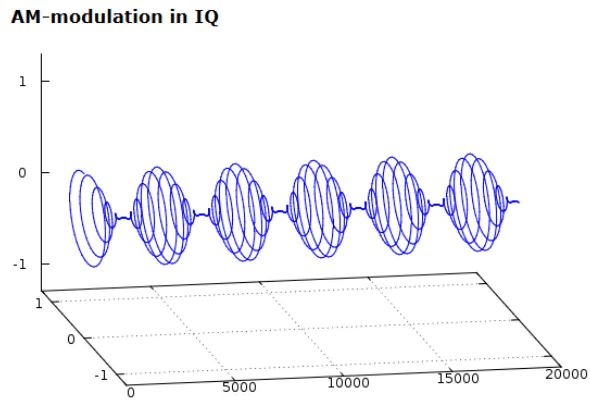

Fig. 33: I/Q Sample Polar Plot of an AM Modulated Signal [Kuisma, 2014]

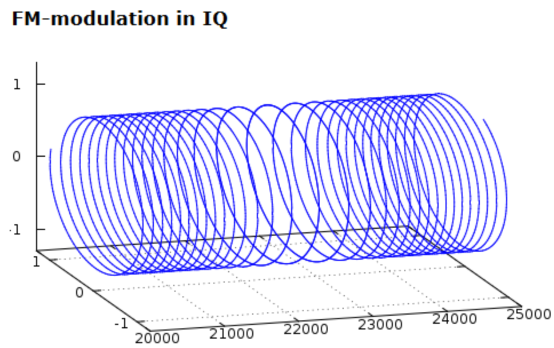

Fig. 34: I/Q Sample Polar Plot of an FM Modulated Signal [Kuisma, 2014]

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