School of Engineering (BH075)

OENG1168 – Engineering Capstone Project

Part B

PASSIVE RADAR SYSTEM USING DVB-T TRANSMITTERS FOR TARGET SURVEILLANCE

Table of Contents:

Supervisor: Paul Beckett

Group: Wednesday 1:30 – 2:30

Submission Date: 14/10/19

Tin Nguyen

s3486352

Abstract

Passive radars utilizes third party transmitters from radio or tv stations to detect moving targets within a certain range depending on the transmitter power. The project aims to determine the suitability of R820T2 register-transfer level software defined radio (RTL-SDR). Subsequently determining its effectiveness in capturing the reference signal and collecting data from Digital Television signals. The evolution of computer processing has enabled greater access to passive radar using SDRs. A fast Fourier Transform using synchronized clocks was implemented to coherently receive radio signals for target detection azimuth and velocity. The capability of the hardware to interpret received data is possible however a real time implementation of data processed is not yet possible due to time constraints and access to high end receivers. The result of the testing shows the peaks of the reference signal but the bandwidth limitations of the DVB-T receivers which proves that cheap SDRs are not suitable to receive DVB-T signals.

1. Introduction

Passive radar (PR) is a radar system that uses a third-party transistor to detect a signal reflected off an object. Passive radar does not emit any electromagnetic waves but rather uses a reference antenna to receive direct waves from the radiation source; passive radars are called illuminating opportunities (IO) due to this reason. Commercial use of passive radar systems started in 1999 with the silent sentry 2 which exploited FM radio stations to detect airborne targets, commercial and private [1].

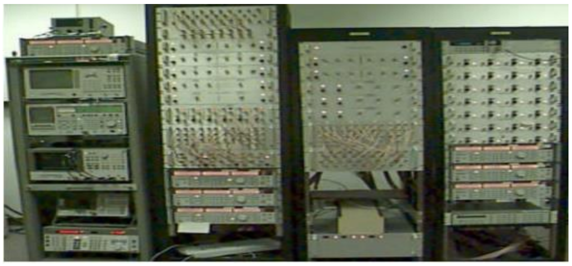

Fig. 1. 1999 silent sentry tm passive surveillance.

The development of passive radar addressed the flaws in active radars which is the accessibility and mobility of a high-powered transmitter. High-powered transmitters come with risks involved to nearby residents and users thus comes with heavy restrictions on its use. Due to technological advancement in the last decade a passive radar dongle has become accessible for use and research. The current DVB-T USB dongle (R820T2) is purchasable online for $20 USD.

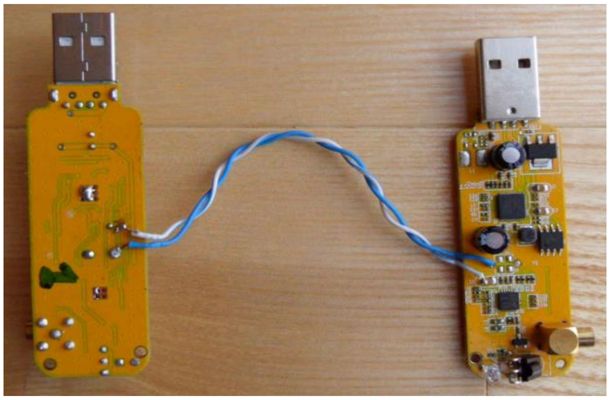

Fig. 2. Making multiple channel receiver from cheap rtl-sdr dongles (r820t). Prerequisite to synchronize clocks of the dongles.

There are 4 main types of IO that is being researched: FM, DVB-T, GSM, and GPS satellite. This research considers (Digital Video Broadcast- Terrestrial) DVB-T signals due to its high resolution, update rate and detection rate as well as high power transmitter. [2].

In modern radar systems there are two main components to which operates in radar systems; the signal processor and the data processor. The signal processor used for target detection and used to distinguish a valid source within a clutter of signals, frequency interference and noise sources/man-made interference. After the signal is finished processing a constant false alarm rate (CFRA) detection fusion must exceed a certain threshold for it to be determined that a target has been discovered [3].

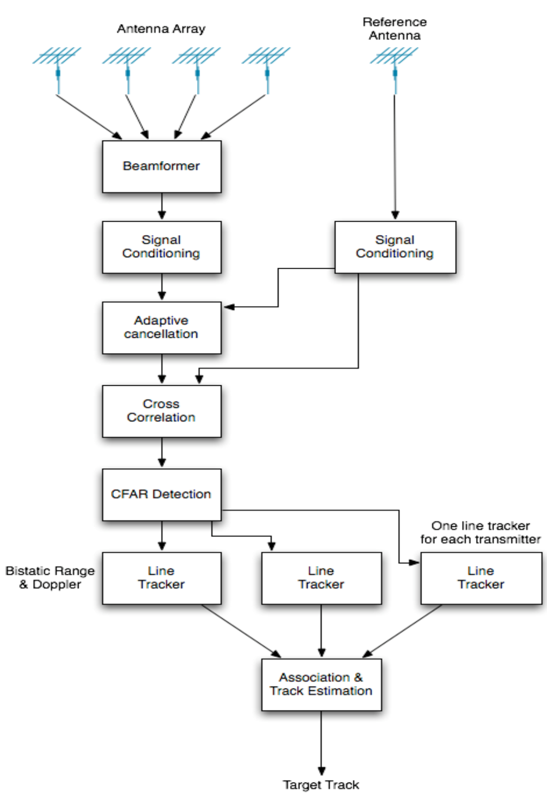

Figure. 3. Passive radar flow chart of operation.

Methodology

The data processor is used as a recording device where its space position, amplitude value, radial velocity and other characteristics parameters of the target are recorded this is usually done by through coding [4]. The data is then processed with tracks, filters, smooths and predicts the objects motion (velocity and acceleration) and position (radial distance, azimuth, and pitch angle). Usually the acceleration and velocity are done through different types of estimation. PR keeps track of the phase of the received signal over time. When a time-varying phase is received there is a frequency shift in the received signal. If the range between the radar and the object of interest is changing, there will be a Doppler shift. Passive Radar has a big advantage when it comes to researching its qualities. The report investigates the hardware components used for passive radar. Mainly the front end of the project dealing with capturing the raw signal rather than simulating one on MATLAB. The popular use of Passive radar for civilian and military use is its cost effectiveness. For our chosen specifications, the frequency range between Ultra high frequency (UHF) and L band is used. Typical UHF spectrums can data stream up to 2.4 million samples per second per antenna with 8-bit resolution; applications of this frequency are used for medium-long range detection, airborne surveillance and weapons detection [5]. Oversampling is used in juxtaposition with high computing power for passive radar to yield range and resolution in junction with low-latency real time operation.

TABLE 1-1 ■ Radar Frequency Bands

Frequency	Range	Example Application(s)
High frequency (HF)	3–30 MHz	Ground-penetrating radar, over-the-horizon radar (OTHR), very long range surveillance radar
Very high frequency (VHF)	30–300 MHz	Foliage-penetrating radar, very long range surveillance radar
Ultrahigh frequency (UHF)	300–1,000 MHz	Foliage-penetrating radar, airborne surveillance radar, long range ballistic missile defense radar
L-band	1,000–2,000 MHz	Weapons location radar, air traffic control radar, long range surveillance radar
S-band	2,000–4,000 MHz	Naval surface radar, weapons location radar, weather radar
C-band	4,000–8,000 MHz	Weather radar
X-band	8,000–12,000 MHz	Fire-control radar, air interceptor radar, ground-mapping radar, ballistic missile–tracking radar
Ku-band	12,000–18,000 MHz	Air-to-ground SAR and surface-moving target indication
K-band	18,000–27,000 MHz	Limited due to absorption
Ka-band	27,000–40,000 MHz	Missile seekers, close-range fire-control radar
Millimeter wave (mmw)	40,000–300,000 MHz	Fire-control radar, automotive radar, law enforcement imaging systems, airport scanners, instrumentation radar

Figure. 4. Radar frequency bands in principles of modern radars.

Channel allocations for Australian DVB-T ranges from 174Mhz to 230Mhz these channels have 7Mhz of bandwidth, previous analog channels are moved to digital radio, the channels are called 6,7,8,9,9A,10,11,12, when the channel is tuned the receiver will choose the center frequency of the bandwidth EG. 174-181 is 177.5Mhz. The theoretical chosen source of illumination is a DVB-T transmitter in Mount Dandenong. With the frequency of 226.5 MHz the ABC channel provides best transmission due to the high transmission power of 50kW and high frequency. Typical frequencies for DVB-T transmitters in Australia are 400-800 MHz and have a bandwidth of 6-8 MHz.

Area Served	Callsign	Frequency(MHz)	Purpose	Antenna Height	Antenna	Maximum	Techni	Licenc	Site Name
Melbourne	HSV6	177.5	Commercial	121	OD	50000	###	##	TXA Eyre Road Site Tower 8 Eyre Road MT DAN
Melbourne	HSV6	177.5	Commercial	164	OD	50000	###	##	TXA Ornata Road Site Tower 12 Ornata Road MT DAN
Melbourne	SBS7	184.5	National	119	OD	50000	###	##	Tower Broadcast Australia Site Eyre Road MT DAN
Melbourne	SBS7	184.5	National	160	OD	50000	###	##	TXA Ornata Road Site Tower 12 Ornata Road MT DAN
Melbourne	GTV8	191.625	Commercial	110	OD	50000	###	##	TXA Eyre Road Site Tower 8 Eyre Road MT DAN
Melbourne	GTV8	191.625	Commercial	163	OD	50000	###	##	TXA Ornata Road Site Tower 12 Ornata Road MT DAN
Melbourne	ATV11	219.5	Commercial	110	OD	50000	###	##	TXA Eyre Road Site Tower 8 Eyre Road MT DAN
Melbourne	ATV11	219.5	Commercial	163	OD	50000	###	##	TXA Ornata Road Site Tower 12 Ornata Road MT DAN
Melbourne	ATV11	219.5	Commercial	119	OD	50000	###	##	Tower Broadcast Australia Site Eyre Road MT DAN
Melbourne	ABC12	226.5	National	160	OD	50000	###	##	TXA Ornata Road Site Tower 12 Ornata Road MT DAN
Melbourne	ABC12	226.5	National	119	OD	50000	###	##	Tower Broadcast Australia Site Eyre Road MT DAN
Melbourne	MGV32	557.625	Community	182	OD	15000	###	##	TXA Ornata Road Site Tower 12 Ornata Road MT DAN
Melbourne Inner	SBS40	613.5	Retransmission	251	DA	270	###	##	Bourke Place 600 Bourke Street MELBOURNE
Melbourne Inner	HSV41	620.5	Retransmission	251	DA	270	###	##	Bourke Place 600 Bourke Street MELBOURNE
Melbourne Inner	ABC43	634.5	Retransmission	252	DA	270	###	##	Bourke Place 600 Bourke Street MELBOURNE
Melbourne Inner	GTV44	641.5	Retransmission	251	DA	270	###	##	Bourke Place 600 Bourke Street MELBOURNE
Melbourne Inner	ATV45	648.5	Retransmission	251	DA	270	###	##	Bourke Place 600 Bourke Street MELBOURNE

Figure. 5. Licensed broadcasting transmitters in Melbourne, Australian Communications and Media Authority, Engineering and Information Services.

System architecture requirements for choosing a passive radar transmitter:

The elevated position of the receiver in Mount Dandenong offers better target detection compared to an active on-site transmitter which is masked by the terrain from buildings, bridges and the ground. These limitations are mathematically equated from the signal to clutter ratio (SCR) Friis free space equation.

$$P_r = P_t \frac{\lambda^2}{(4\pi)^2} \frac{G_t G_r}{R_{tr}^2}$$

The received power Pr of the direct path can be calculated using the Friis free space transmission equation: where Pt is the transmitter power; λ is the wavelength of the transmitted waveform; Gt is the gain of the transmit antenna in the direction of the receiver; Gr is the gain of the receive antenna in the direction of the transmitter; Rtr is the distance between transmitter and receiver. The equation shows the inverse proportional relationship between the Power transmitted and the range loss Rtr. Thus, when choosing a transmitter there must be consideration to the transmitter power since the loss of range to the target is to the power squared.

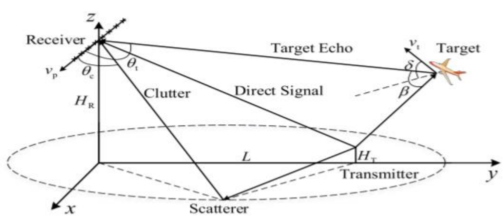

Fig. 1. Airborne passive radar geometry.

Figure. 6. Airborne passive radar geometry.

The mathematical equation of the system assume that both the receiver and the transmitter antenna are isotropic and can be represented in decibels unit below [6].

$$\mathrm{P_r}(dbm) = 10\log_{10}\frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} + 30$$

$$P_r = 50000W\,\frac{1}{(33{,}000m)^2}\frac{0.462286^2}{(4\pi)^2}$$
$$= 5e^{-8}W\ (-32.92dBm)$$

Upon calculation of the decibel gain of Pr the gain seems pretty low and thus another transmitter was chosen, since the retransmission broadcast tower is on Bourke street with high frequency, calculating approximation of the range can be set to 100 meters although the transmitter has a low 270W power output.

$$P_r = 270W\,\frac{1}{(100m)^2}\left(\frac{3.0*10^8}{4\pi*648.5Mhz}\right)^2$$
$$= 3.65e^{-5}W\ (-14.366dBm)$$

From the conclusion if the area tested is directly under Bourke street there should be a better gain, however the effective range is only 100m. The high transmission frequency (λ) and low range loss (Rtr) compensates for the low emitted power (Pt).

Passive radar FFT

In active radar systems, since the transmitter emits a pulse signal, the signal can be cross correlated with the reflection of the return signal. This approach called uses the match filter. Within passive radar the emitted signal is masked; since it is a third-party transmitter the shape of the transmitted signal is unknown and the received signal shows six reflected peaks even though there are only 2 reflections in the example below.

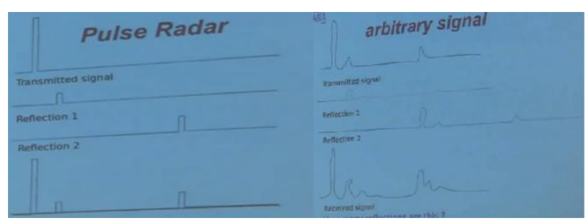

Figure. 7. Example of Active radar transceiver to a passive radar transceiver.

For passive radar 2+ measurement antennas are needed compared to needing 1 for active radar. In passive radar, the reference antenna is used to measure the direct wave from the IO. The second antenna is the measurement antenna used to obtain reflections from static or moving targets. These 2 measurements are then cross correlated to give a similar result to the matched filter approach. However, synchronization of the frequency, time, and phase of the two signals is crucial for a proper cross-correlation.

Fast Fourier Transform

Cross correlation is similar to the Fourier transform convolution theorem, where (t) is time and (τ) is the displacement also known as lag [7]. Cross correlation of a deterministic signal can find how much the reflected signal has been shifted across the x axis to make it identical to the reference signal.

Convolution formula:

$$conv(s,r)(\tau) = \int s(t)r(\tau - t)dt$$

Practical formula for computing convolution:

$$FT\big(conv(g,x)\big) = FT(g) * FT(x)$$

Correlation:

$$corr(s,r)(\tau) = \int s(t)r(t+\tau)dt$$

Since

$$\exp(j\omega t)^* = \exp(-j\omega t)$$

We can see that convolution is correlation has time flipped, the relationship between correlation and computation results in calculating the complex conjugate FT.

$$FT\big(corr(g,x)\big) = FT(g) * FT^*(x)$$

The formula essentially slides the reflected signal along the x-axis, calculating the integral product at each position.

The practicality of the correlation can be later seen in the waterfall diagram as known as Radar Spectrogram to show that each frequency has a unique frequency signature similar to a sonogram.

Findings/Discussion of results

Creating passive radar device

The project aims to get real time data from a cross correlated signal between a flying unmanned armed vehicle (UAV) and the reference channel transmitted from either Bourke street or Mount Dandenong. The type of product used will be the Register Transfer Level, Software Defined Radio (RTL-SDR). For the experimental project two 2013 R820T2 chip containing the digital demodulator will be used to obtain frequency synchronization.

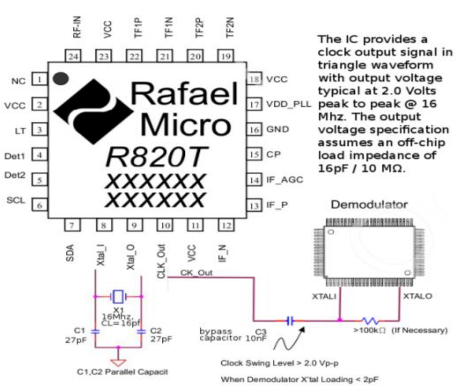

Figure. 8. RTL-SDR Clock Configuration (Superkuh 2016)

As previously explained, proper cross correlation requires mandatory synchronization in frequency, time and phase. Since each dongle is clocked by its own quartz oscillator, a simple solution is to unsolder Crystal Oscillator (8.) and connect it to the frequency source of the other device. The function block diagram helps understand where to connect the frequency clocks for frequency synchronization. As a result, the master DVB-T receiver (xtal_i 8.) is connected to the slave DVB-T receiver (10 clk_out).

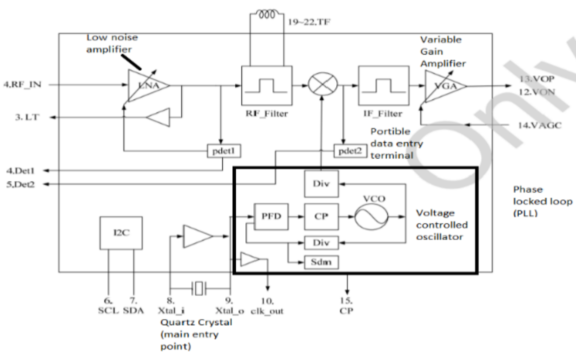

Figure. 9. Simplified R820T Block Diagram.

PLL Dithering

RTL devices requires excellent control functionality and accuracy of the carrier. The precision of the local oscillator lies in its phase locked loop control system which helps tune to the clock to the exact frequency by using dithering. Without dithering the tuning chip can only tune in increments of 439.45 Hz due to its 22 bit fractional PLL register in the modulator chip and the 16 bit fractional R820T chip.

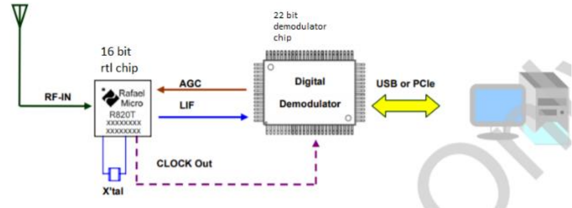

Figure. 10. R820T datasheet, Figure A. Example of DTV reception for PCTV applications.

Due to the mismatch between the two chips the set frequency cannot be exactly tuned to the end frequency without margin of error. Dithering applies a form of randomized noise using quantization error to average the frequency steps but introduces phase coherence loss [8]. For the purpose of frequency synchronization however removing dithering is required and is addressed within the rtl library codes.

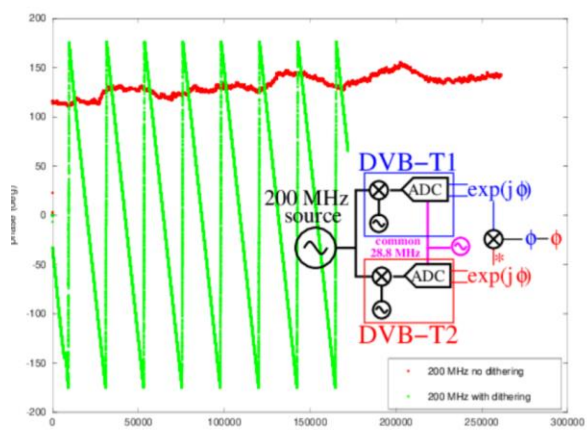

Figure. 11. Impact of dithering (green active, red deactivated) on the phase difference between the output of two DVB-T receivers fed by the same oscillator (JMFriedT).

Implementation of two frequency locked oscillators.

Due to the size of the RTL chips (2x6cm), the stability of the two devices become a concern, since the base needs to be removed to connect the 2 sdr together a new base is also needed for conduction purposes.

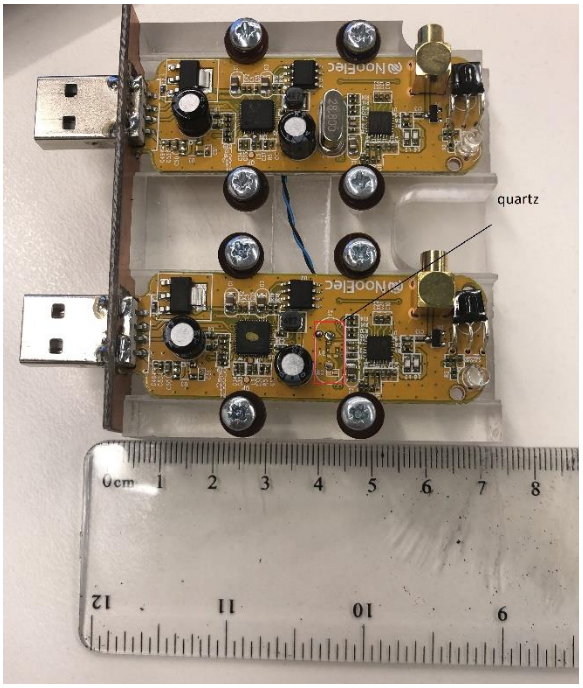

Figure. 12. 2 RTL-SDR boards connection implementation.

The acrylic board serves as an anti-conduction base while the standoffs holds the board together for testing purposes. Two wires connecting to ground and the clock as seen in the picture the quartz is removed to mimic the master-slave clock synchronization.

Removing dithering and testing

Since most of the development of rtl-sdr is on Linux system, the use of Ubuntu terminal is necessary. Programming is done without a GUI but purely through terminal and done through many guides online. However, many of the guides do not factor in the removal of dithering and multiple connected dongles which makes it difficult to implement certain functions that is implemented in one code but not the other.

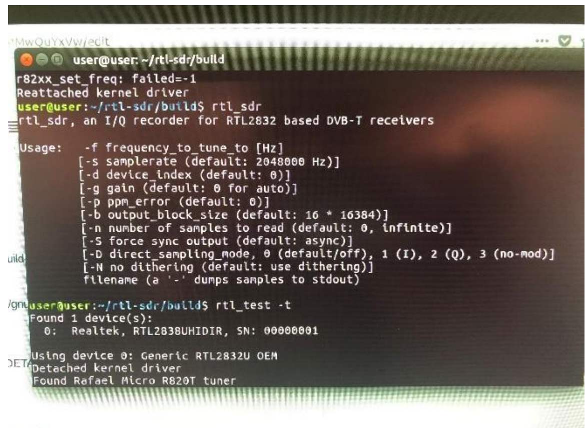

Figure. 13. Command line rtl tests, showing no dithering

The frequency dithering is active as a default configuration shown in the code above. It can be disabled however the code also disables the use of multiple SDR. Testing the reference signal did not require both dongles to be active so the problem can be rectified later on with more code implemented. Temperature drift can be tackled by providing a thermal link between the two receiver front ends, however data proved no difference in frequency.

RTL_power and time offset calibration

RTL_power addresses the second challenge to DVB-T passive radar. The time synchronization of the two USB dongles are not synchronized from the time of is received at the demodulator and at the connection of the two USB ports may result to time differentiation. Due to the time offset between the two USB, offset calibration is needed, however if the data stream is stopped and disconnected, another re-calibration is needed.

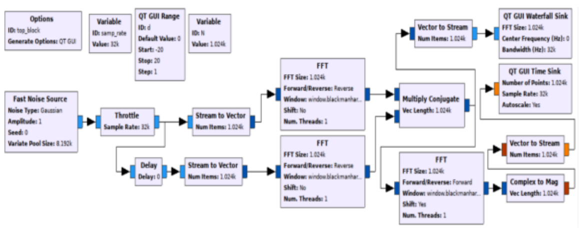

Figure. 14. GNU radio time calibration from local noise source. (fosdem 2018 presentation on passive radar)

GNU radio addresses the sampling time differences relative to each other by disconnecting the antennas from the receiver and connecting every receiver to the same noise source. Cross correlation of the noise source gives the time and phase difference so it can be corrected.

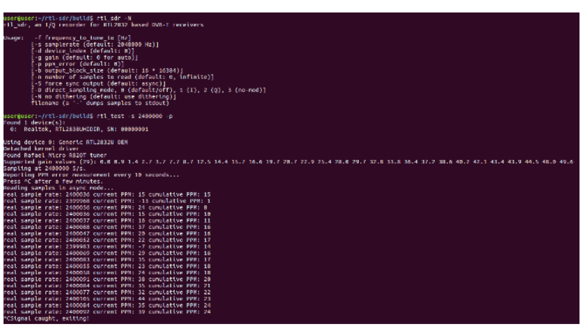

Figure. 15. Time calibration ppm error. 2.4Mhz frequency check.

The temperature compensated oscillator shows low frequency error drops after disabling dithering compared to Appendix 4. Thus, the time offset can be seen as constant and no sample loss is observed. The time offset between the two streams is to be observed to be most at ±500 µs range.

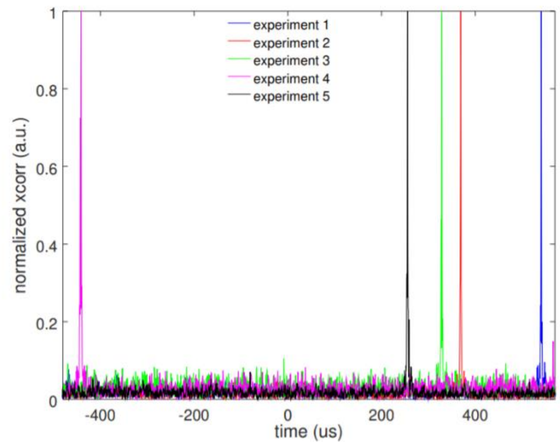

Figure. 16. Normalized cross correlation when connected to the same noise source: the time delay varies but remains in the ±500 µs range.

RTL_power allows continuous data stream wideband multiday stream compiled into a spectrogram without needed calibration. The disadvantage of a continuous stream compared to only collecting batches of data is the limited allocated disk space, According to J.-M Friedt "the data stream for moving aircraft is limited by the data bandwidth which requires storing data in RAM at 2MS/s, 4 bytes/sample which equates to the data rate of 32MB/s or 1.92 GB/min." and W. Sun dissertation states that system performance is limited to primary network bandwidth as well [9][10].

Another advantage of RTL_Power is its adjustable frequency bin size which is a segment of frequency collected and usually smaller can observe multiple peaks and closely observe more reflections from the signal.

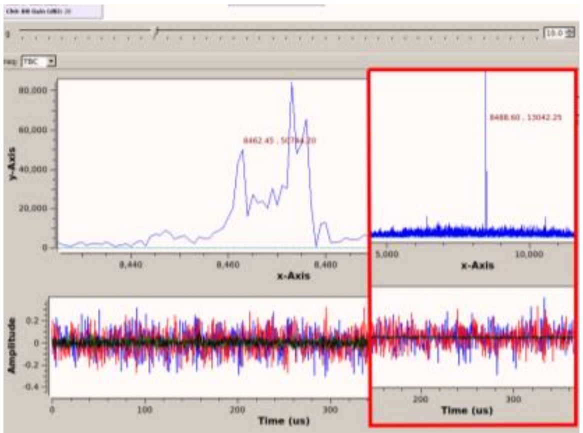

Figure. 16. GNUradio use of multiple frequency peaks using a small bin size.

RTL power and spectrogram

When using the software there were some complications involved for testing. Firstly, the weak antenna provided by the package did not give strong gains, however RF lab room no longer had large antennas for testing according to my supervisor "It was removed.", appendix 1 contains 2 csv files for numerical data for each sample collected while the png is the data converted into a spectrogram. The chosen bin size was 10kHz and 50khz which means each pixel is 10khz/50khz wide for 10 seconds long. Lower bin size gives better resolution of the peaks however when lowering the bin size under 10khz the SDR is not efficient enough at that particular resolution, giving demodulation error when writing to the demodulator chip.

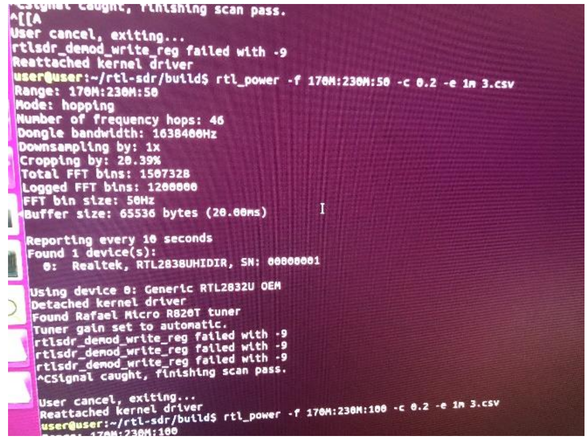

Figure. 17. Demoulation error for low bin sizes.

When analyzing the peaks at the DVB-T radio stations, we can see the peaks same to figure. 16. However, since the bin size of the modulator gives a frequency bandwidth of 1.28Mhz and the frequency of the DVB-T station bandwidth is 7mghz. We can confirm that there is a signal there but cannot be analyzed and used for passive radar.

GQRX

Another program was used to check the waterfall to rule out any faulty software problems. With this program a graphic spectrum analysis can also be seen and is much neater than rtl_power. The same results can be seen in the frequencies however when testing FM radio stations, a signal can be picked up however it has low gain. Test results showing the peaks are not on the central frequency but offset, however this can be due to software calibration error. Refer to data in Appendix 2.

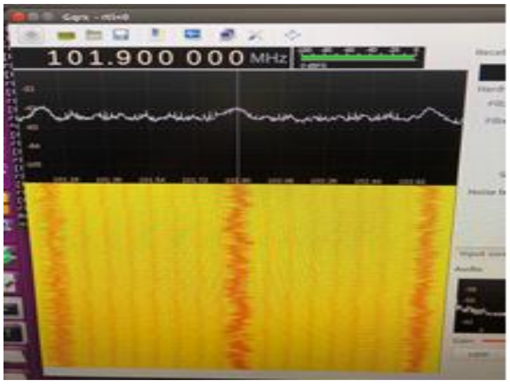

Figure. 18. GQRX FM radio frequency gain.

DVB-T channel testing,

Future testing for a DVB-T signal resulted in failed attempts compared to the YouTube guide "TV Technology - Part 3 - Linux DVB-T Adapter Install". This can be the results of the weak antenna gain.

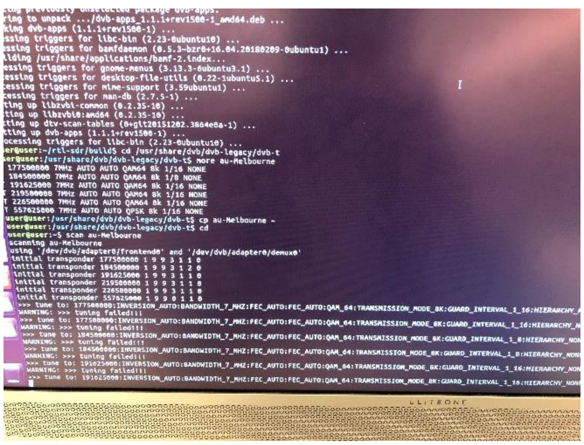

Figure. 19. DVB-T channel test failed attempt due to weak antenna gain.

Conclusion/Future work

Using the low-cost consumer grade DVB-T receivers for the application of Passive radar is unsuitable for DVB-T frequency purposes and remains only for passive radar using an FM transmitter. The technical process further helps to achieve raw data coming from the RTL-SDR dongles rather than simulated results obtained from oscilloscope. The processing steps were successful to build a DVB-T receiver namely: feeding both receivers with a common clock and tuning the phased lock loop to disable dither, Calibration of the time off-set between the 2 DVB-T receivers and so forth. The time offset between the two data stream remains constant and calibration is due to the modulator to USB-bus data transfer time offset. Despite the low resolution of bandwidths tested with RTL_power signals in that frequency is identified to be correct in conjunction with the (ACMA) data. Extending the setup to include better gain and more antennas will result for more resolution in azimuth as well as velocity detection. The project is far from the capability of real time correlation processing on the FPGA board and collision detection.

Future Work

Continuing the project from week 12 will involve both hardware and software improvements such as: a working tv demo by obtaining a high end sdr for comparison to the consumer grade R820T2. Receiving fund to buy high gain antennas for better results. Troubleshooting multiple rtl-sdr is also required since currently there is a problem with the USB listening to the sdr and dvb-t the two chips are interfering. MATLAB has a program to observe the data input of the sdr for cfra and correlation. Collision detection and moving target can be utilized from furthering the project when real time data is collected from MATLAB results. In this project we attempted to recreate passive radars using cheap dvb-t receivers, exhibiting the technical steps to develop an experimental setup. Recreating a clock and tuning phased locked loop to disable dithering. Further research in GNUradio can be helpful for fast prototyping and educational purposes.

Risk assessment & Project Planning

The project is deemed low risk, but to ensure the project is undertaken in a safe and appropriate environment; identifying hazards subsequently outlines a risk management strategy. There are 4 four risk activities: soldering/modifying the hardware to obtain frequency synchronization, frequency radiation emitted from nearby transmitter when testing on Bourke street and future testing at Mount Dandenong, operating and testing in public places, transporting hardware to appropriate testing locations in a vehicle. Soldering was done in a well-ventilated environment due to the lead contents in solder. Washing hands after handling solder reduces the risk of lead poisoning in case of handling food after the experiment. Radio Frequency (RF) radiation can cause burns and internal injuries according to the Australian Radiation Protection and Nuclear Safety Agency (ARPNSA) [11]. The falloff distance of the radiation with the use of perimeter fences in Mount Dandenong deems it safe when testing. Operation of testing equipment: large antennas and laptop can result in trip hazards in a public space when collecting data. To ensure public safety perimeter fences is useful can ensure of any trip hazards. The use of motor vehicle is required to test signal strength. The risk can be managed by abiding road rules.

Project Timeline

A Gantt chart was created and can be viewed on GitHub via appendix 3 link.

References

[1] J. Baniak, G. Baker, A.M. Cunningham, L. Martin, “Silent Sentry™ Passive Surveillance,” Aviation Week & Space Technology, June 1999.

[2] Hermann Rohling Krzysztof Kulpa. Defense and Security Research Center . <https://slideplayer.com/slide/3432556/> viewed on 11/08/2019.

[3] Y. He, J. Xiu and X. Guan, *Radar data processing with applications*, 2nd ed. John Wiley & Sons, 2017, pp. 1-2, 466-467.

[4] He, Y., Guan, J., Meng, X., et al. 2011. Radar Target Detection and CFAR Processing, 2nd edn. Beijing: Tsinghua University Press.

[5] Richards, M. A ; Scheer, Jim ; Holm, William A ; Melvin, William L. 2010. Principles of modern radar: basic principles, 1st edn. Institution of Engineering and Technology.

[6] P. Bevelacqua, "Antenna Theory - Decibel Math", Antenna-theory.com, 2019. [Online]. Available: http://www.antenna-theory.com/definitions/decibelMath.php. [Accessed: 09- Oct- 2019].

[7] L. R. Rabiner, B. Gold, Theory and Application of Digital Signal Processing, New Jersey, United States, Prentice Hall, 1975.

[8] V. profile, "GNSS carrier phase, RTLSDR, and fractional PLLs (the necessary evil)", *Michelebavaro.blogspot.com*, 2019. [Online]. Available: http://michelebavaro.blogspot.com/2014/05/gnss-carrier-phase-rtlsdr-and.html. [Accessed: 11- Oct- 2019].

[9] W. Feng, G. Cheranki, J-M Friedt, M. Sato "Software defined radio implementation of passive RADAR using low-cost DVB-T receivers," Feb 2018

[10] W. Sun, "High Speed Passive Radar Receiver with Application to Digital Television Signals," Ph.D. dissertation Electrical Engineering University of Washington, USA, 2017, Accessed on 13 October, 2019. [Online]. Available:https://www.researchgate.net/publication/323557904_High_Speed_Passive_Radar_Receiver_with_Application_to_Digital_Television_Signals

[11] ARPA, "Maximum Exposure Levels to Radiofrequency Fields — 3 kHz to 300 GHz," Radiation Protection Series, vol 3, March 2002, Accessed on 14/10/2019. Available: https://www.arpansa.gov.au/sites/g/files/net3086/f/legacy/pubs/rps/rps3.pdf

Appendix

1. RTL_Power software results and waterfall diagram. https://github.com/RMIT-TIN-N-H/rtl-power-results-and-data
2. GQRX DVB-T results https://github.com/RMIT-TIN-N-H/rtl-power-results-and-data/tree/master/gqrx%20images
3. Gantt Chart https://github.com/RMIT-TIN-N-H/rtl-power-results-and-data/tree/master/gantt%20chart%20copy
4. PPM time frequency offset calibration https://github.com/RMIT-TIN-N-H/rtl-power-results-and-data/tree/master/ppm%20time%20offset%20calibration