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LOW-COST, SOFTWARE DEFINED FMCW RADAR FOR OBSERVATIONS OF DRONES

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JIAXI ZHU
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LOW-COST, SOFTWARE DEFINED FMCW RADAR
FOR OBSERVATIONS OF DRONES

A THESIS APPROVED FOR THE
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

BY

_____
Dr. Yan Zhang, Chair

_____
Dr. Joseph P. Havlicek

_____
Dr. John W. Dyer

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Abstract

This thesis focuses on implementing a small, low-cost, Frequency-Modulated-Continuous-Wave (FMCW) radar sensor using Software-Defined Radio (SDR) platforms. Extensive investigation and comparisons of existing SDRs are provided. Two of the sensor platforms are tested using both commercial FMCW radar kit and USRP-N210 radio. The main application of the effort will be detecting small unmanned aerial vehicles (UAVs) using low-cost, reconfigurable FMCW radar sensors. Simulation studies of various SDR system configurations are done in MATLAB, and hardware calibration using loop-back testing is performed. Detailed discussions on system performance predictions and enhancements, as well as design considerations, are provided. The implemented sensor systems are then brought to outdoor experiments with targets such as reflective plates, water-towers and small drones.

Chapter 1: Introduction

1.1 Continuous Wave Radar

A radar system transmits and receives either pulsed or continuous waveforms for target detection, tracking and imaging. Such a system usually contains antenna, electronics, control system and operators, as shown in Figure 1. One way to categorize radar systems is based on the transmitted waveform (pulsed or continuous wave). Both types of radars are able to perform all the radar functions.

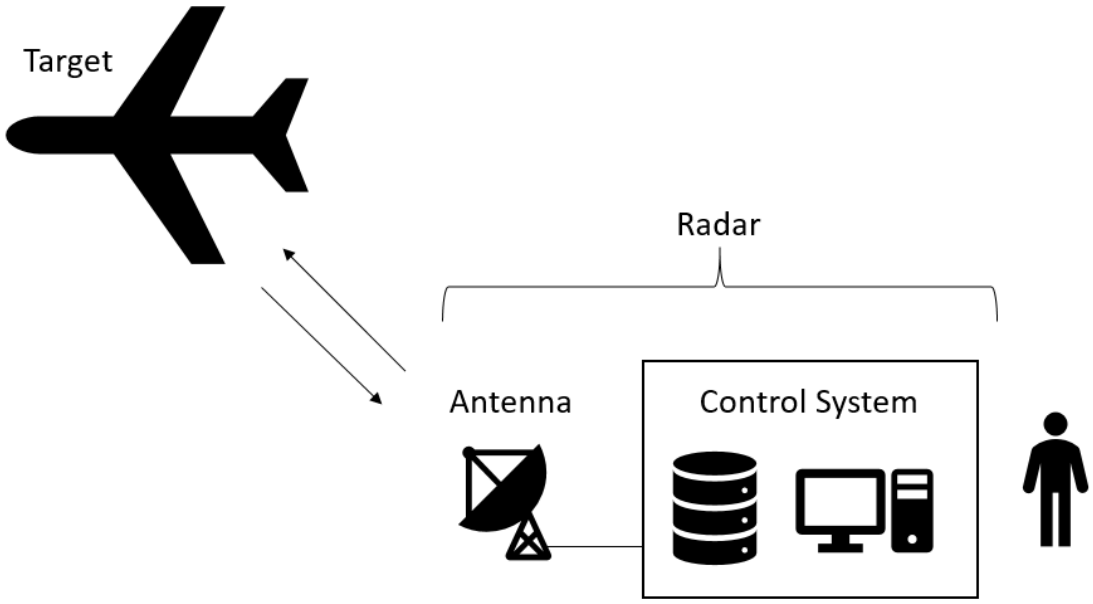

Figure 1. General concept of radar system operations

A pulsed radar transmits a pulse signal with short duration at some configured time-interval. Target echoes are received during intervals of the transmission. Using measured delays from transmission to reception of target signal, the distances of targets can be determined.

A continuous wave (CW) radar, on the other hand, transmits the signal and receives the signal simultaneously. CW radar with single tune transmission is good for Doppler

and angle measurements, but is not capable of ranging or multiple target observation. FMCW (frequency modulated continuous wave) radar is a special kind of continuous wave radar that combines linear frequency modulation to the radar carrier wave, thus allowing range measurements. However, FMCW radar has limitations similar to pulsed radars, which will be discussed later. FMCW radar has a wide range of applications from police speed radar and radar altimeter, to low-cost, small-sized motion sensors in automobiles. In this thesis, we focus on the implementation of FMCW radar functions in a software-defined platform and its use applications described in the following section.

1.2 Application Background

With the fast development of low cost electronic devices in recent years, small unmanned aerial systems (sUAS) have become more popular in the consumer market. It can cost approximately several hundred dollars to get a sUAS from a local store or an online shop. However, due to the increasing number of sUAS, it is becoming common for sUAS to easily intrude into private places or restricted areas. For example, in 2017, a drone hit the top of Space Needle in Seattle [1]. There are also reports of drones flying close to airports, which can threaten passenger airplanes [2].

As a result, The Federal Aviation Administration (FAA) and law enforcement are implementing several laws and regulations to monitor and regulate sUAS operation in the national airspace. For example, the FAA recently published an official set of sUAS rules [3]. According the initial rules, sUAS operated under this regulation cannot exceed 55 lbs in weight. sUAS must be in sight of the operator or the observer at all times (maintain line of sight), and the maximum ground speed is 100 miles per hour. The maximum

altitude of sUAS is 400 feet from ground level and they cannot fly within a 5-mile radius of an airport. The actual operation profile of sUAS is very complicated and is depicted in Figure 2. Sometimes the operation of small drones is not compliant with the FAA Small UAS regulations, such as military operations, beyond line of sight and night operations, as well as illegal usage. Therefore, sensor technologies need to be developed to improve tracking and identification of such drone flights.

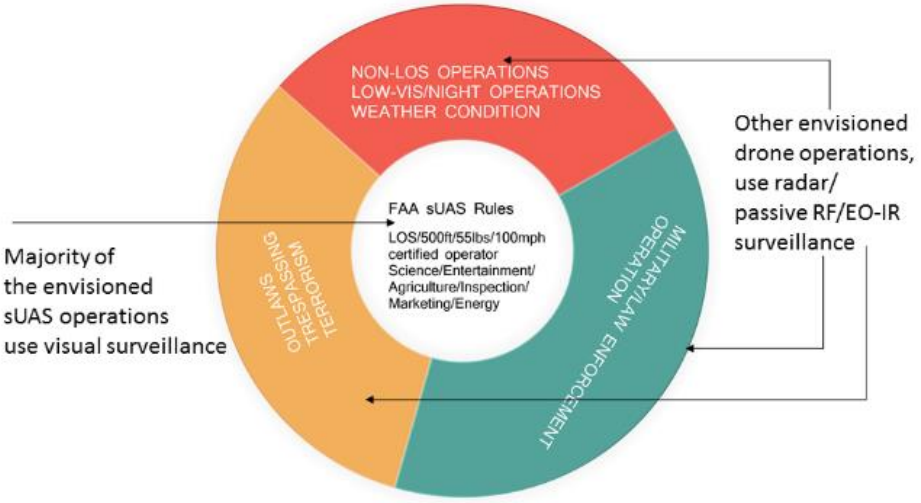

Figure 2. "Background of civilian counter drone operations" [4]

Counter-drone technologies have been developed in military applications. For example, counter-drone jammers have been used before, which target the communication and control links of the drones [5].

Before employing countermeasures, it is crucial to detect and track the positions of the drones. The detection can be done using human visions, cameras, radars and spectrum sensing [4]. Figure 3 shows the time-spectrum of a type of drone's RF link. Based on the

features of this spectrum, one may be able to detect and identify a drone's activities. However, due to the small size and the "bird-like" flight behaviors, it is usually very difficult to perform such detection reliably using one single type of sensors.

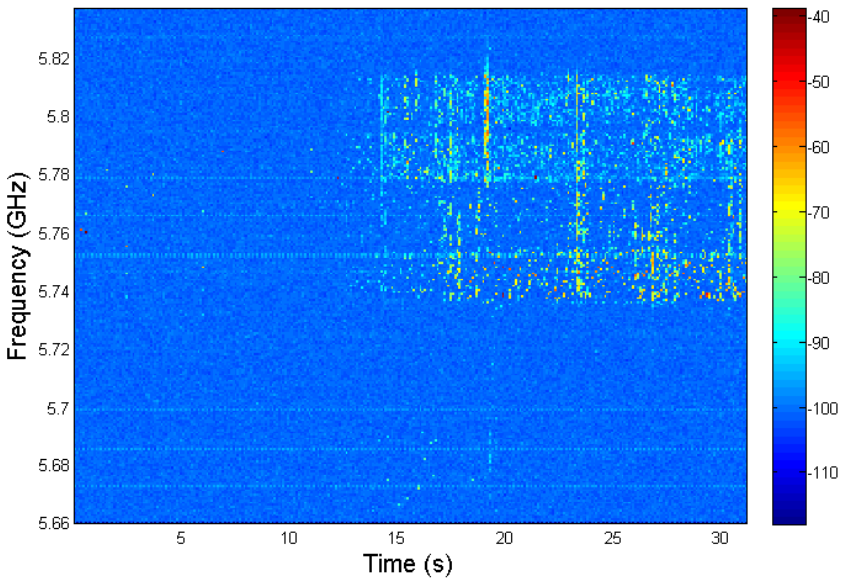

Figure 3. "Time-spectrum of a 5 GHz small drone data link (turned on at 15 secs)"[4]

In this study, we focus on using software-defined radar (SDR) for detection and possible classification of small drones. SDR offers smaller hardware size and more flexibility for performing multiple functions. The SDR can be used to execute other functions, such as spectrum sensing, during the same time of radar operation. Thus, FMCW radar provides a low-cost, low power radar sensor that can provide detection and tracking of small drones, while potentially providing other functions like spectrum sensing.

1.3 Software Defined Radio and Radar

Software-defined radio (SDR) has existed in various forms for more than 30 years: the phrase “software radio” was first made by E-Systems company in 1984, and the GNU Radio was built in 2001 [6].

Currently, SDR has a broad range of applications in many different areas. For example, in telecommunications, SDRs have been used to implement base stations or other services such as LTE [7]. It is also used for implementing GNSS receivers [7]. Furthermore, SDRs have been used for radar development.

Software-Defined Radar (SDR) is closely related to Software-Defined Radio (SDR) [8]. Both of them share certain common hardware platforms, but execute different functions. Radar implementations usually require a co-located transmitter and receiver, real-time processing, and estimation of target states. For the remainder of this document, the term SDR will refer to software-defined radar. It will be made explicit if software-defined radio is being discussed.

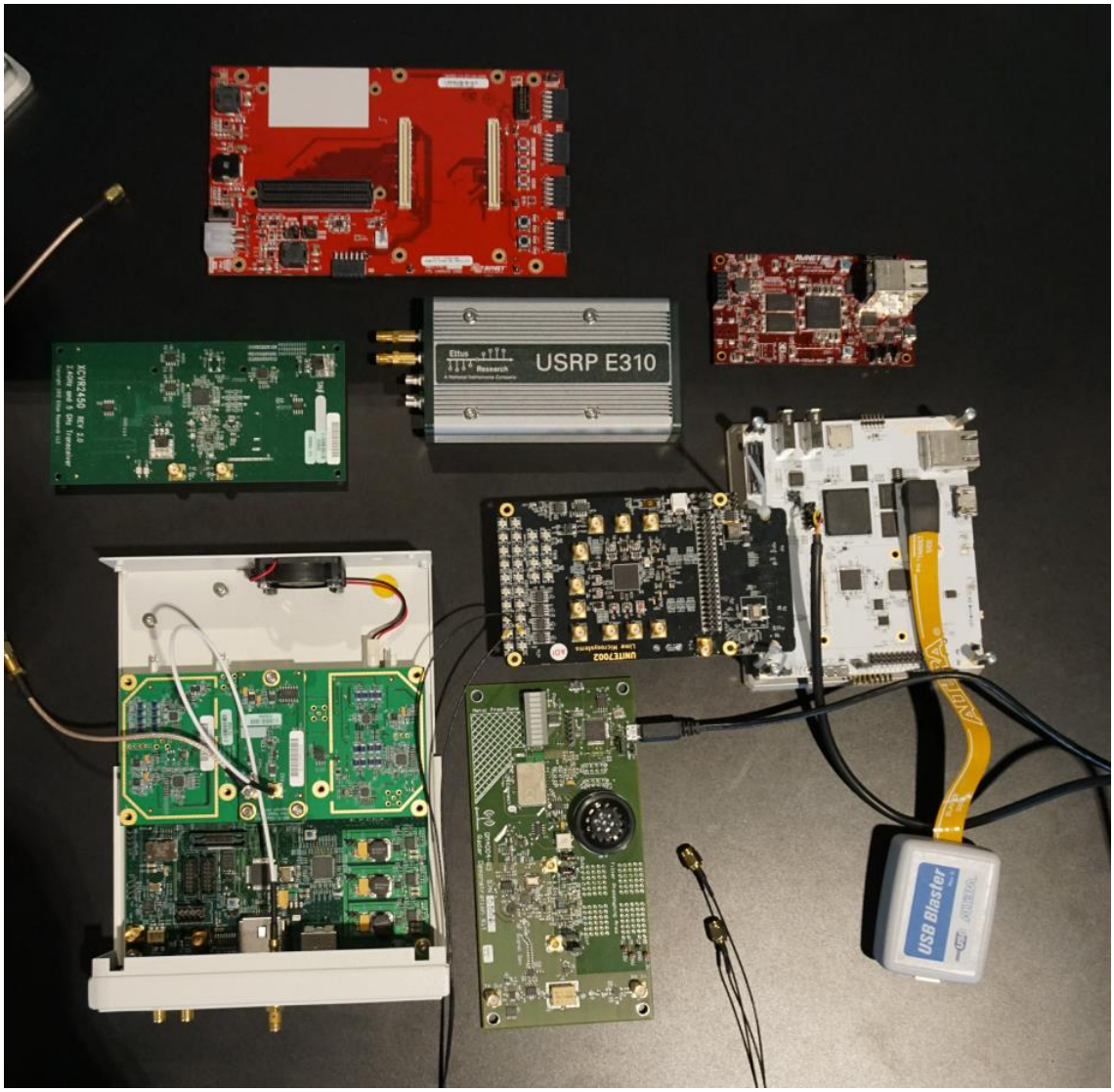

Figure 4. SDR hardware

An advantage of SDR is that real-time software can implement many radar processing functions, such as correlation, filtering, etc. Since these functions are usually implemented using hardware components in traditional systems, using SDR can save cost and add degrees of freedom. The system can be reconfigured easily, is much more flexible, and less subject to hardware issues such as phase instabilities in the analog RF circuits. This is part of the motivation for this thesis.

As a key component and tool for SDRs, the following Figure 5 and Figure 6 show some components of the software development kit of the GNU Radio companion, which is the main software development tool used in this work. The GNU Radio is an open-source software-defined radio programming interface, which is independent of the hardware platform and can be reused through adding system-specific modules [8].

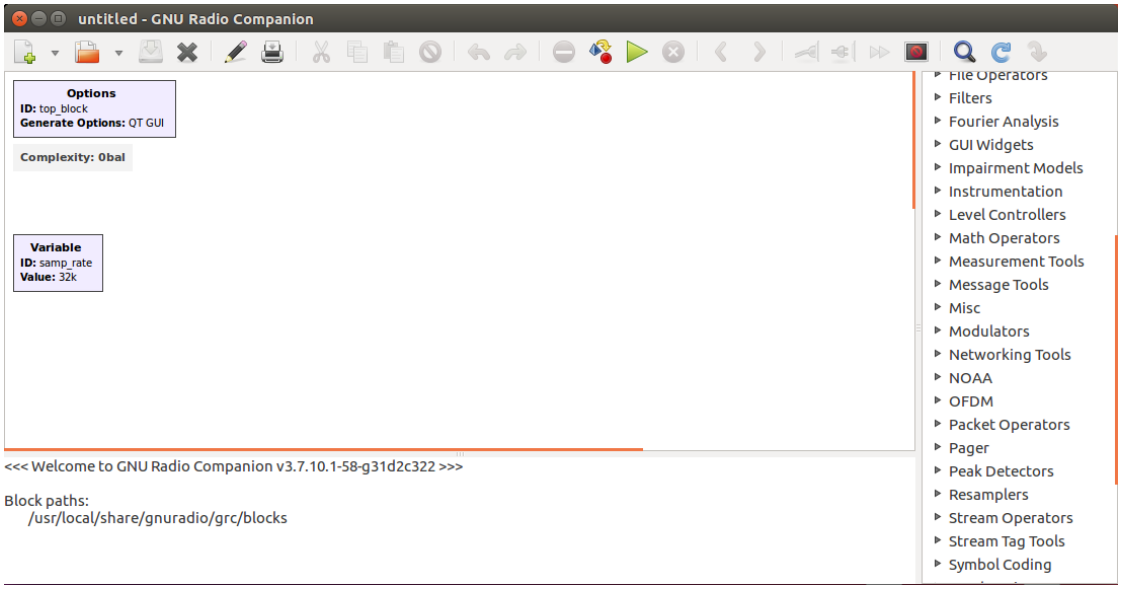

Figure 5. GNU Radio Companion software in Ubuntu

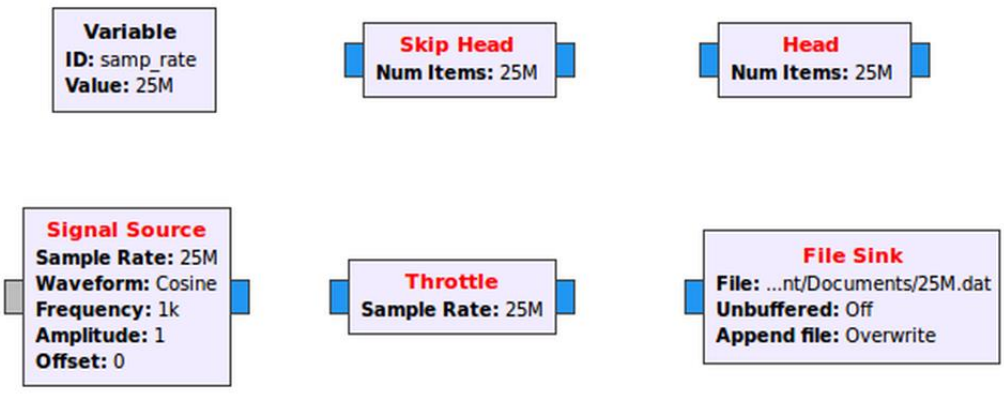

Figure 6. GNU Radio Companion blocks

1.4 Outline of Thesis

Chapter 2 will discuss detailed operational principles of FMCW radar. It describes the basic concepts about FMCW radar, like the system diagram, FMCW waveforms, processing algorithms and so on. The key system parameters of FMCW radars affecting performance are also discussed.

Chapter 3 summarizes the investigation of different Software-Defined Radio (SDR) platforms in market. These platforms include STREAM board and UNITE7002 kit, MicroZed kit, USRP E310, USRP N210 and WBX, QM-RDKIT. The main features and performance of these platforms are compared, then the most appropriate platforms are selected for the studies in this thesis.

Chapter 4 focuses on the outdoor experiments. The detailed experimental setup and procedures are discussed, then the measurement results obtained from specific SDR implementations (QM-RDKIT kit and the N210 kit) are presented.

Chapter 5 summarizes the work of this thesis and contributions. This chapter also discusses the proposed future work. The recommended improvements include three aspects: antennas, software and signal processing algorithms.

Chapter 2: Operational Principle of FMCW Radar

2.1 System Architecture

In the transmitter of an FMCW radar system, the FMCW signal generator performs frequency modulation and produces transmit waveforms. The FMCW waveform is amplified in the transmitter and the electromagnetic waves are sent through the TX antenna to the air. The electromagnetic waves will be reflected by the target object. Then the RX antenna receives the reflected waves from the target, which are processed by a low-noise amplifier and then mixed with a copy of the transmit FMCW waveform. Mixing the transmit and receive waveforms effectively down-converts the frequency difference to the baseband, allowing the A/D converter to sample at lower rates. After mixing, an analog-to-digital converter (A/D converter) samples the mixed signal, and the sampling data is stored in the data file. The data file can be processed in real-time or imported to software tools for off-line processing.

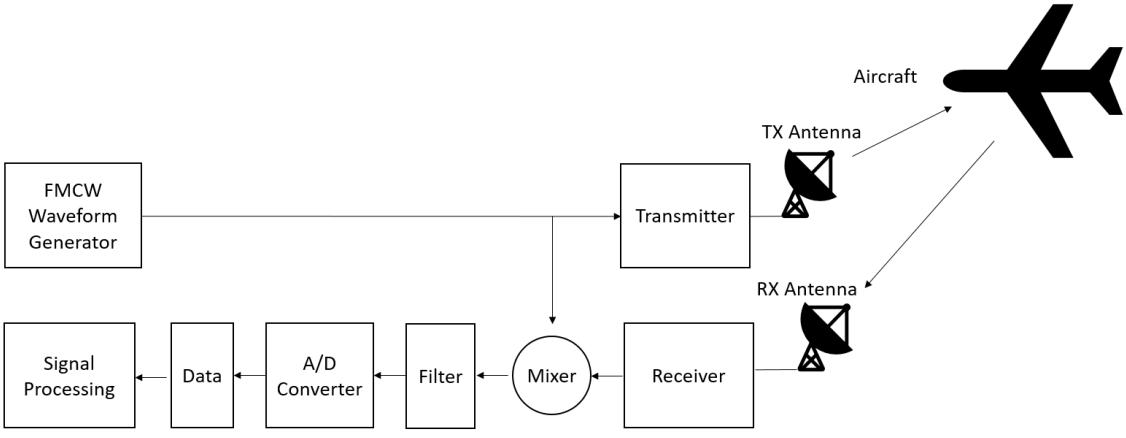

Figure 7. Simplified diagram of an FMCW Radar system

2.2 FMCW Waveform and Fundamental Features

As mentioned in Chapter 1, FMCW is short for frequency modulated continuous wave. Figure 8 is the picture of a single-tone continuous wave in time domain. They are sine or cosine waves in a constant frequency. In other words, the frequency of continuous waves does not change at all, as shown in Figure 9.

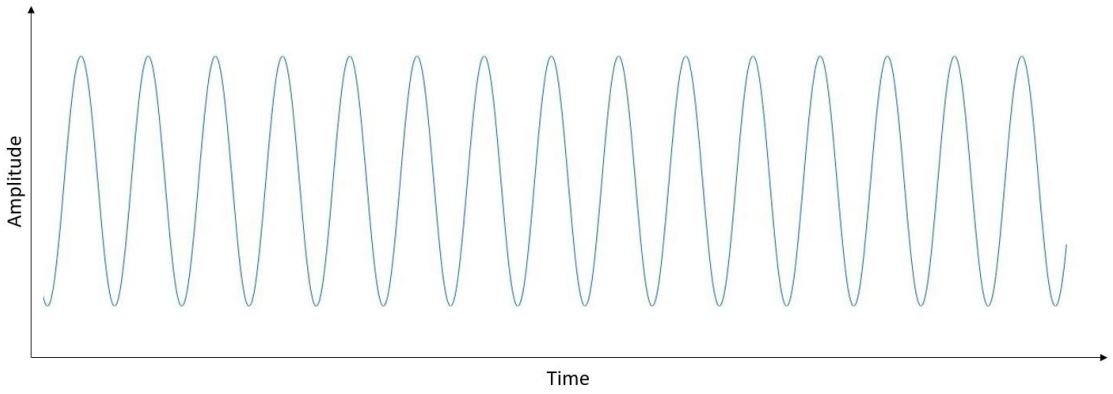

Figure 8. Time-domain plot of a simple continuous wave (CW) Radar waveform

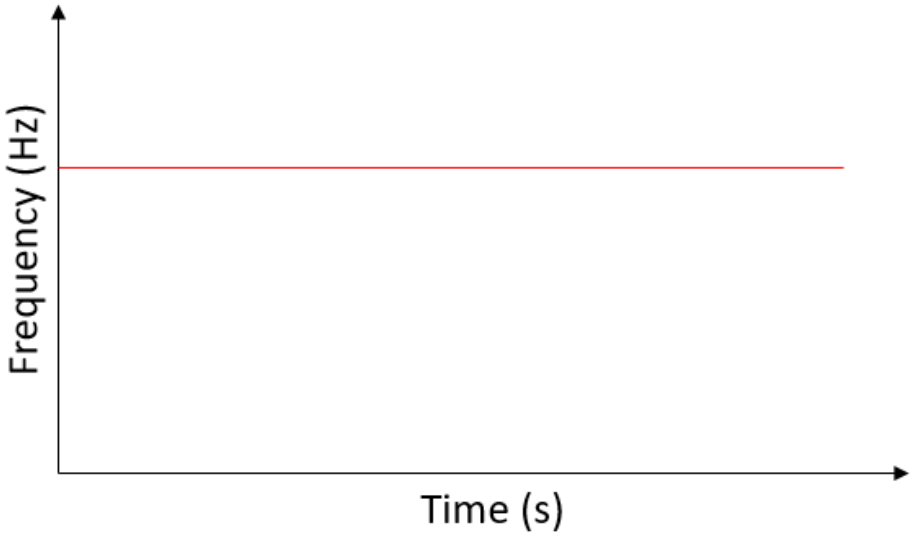

Figure 9. Time-frequency plot of the simple CW waveform

FMCW is a kind of linear frequency modulated waveform that covers wider frequency bands. In one sweep period, FMCW frequency is changing with time linearly, as in Figure 10. In the time-domain, Figure 11 shows the linear increasing of the modulation frequency of FMCW waveform.

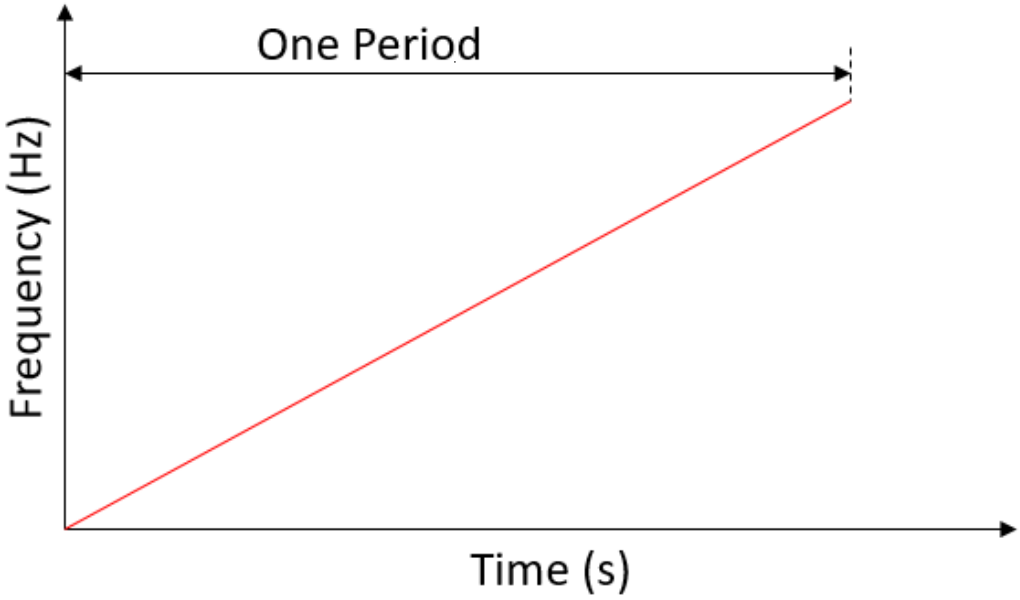

Figure 10. FMCW wave time-frequency plot in one period

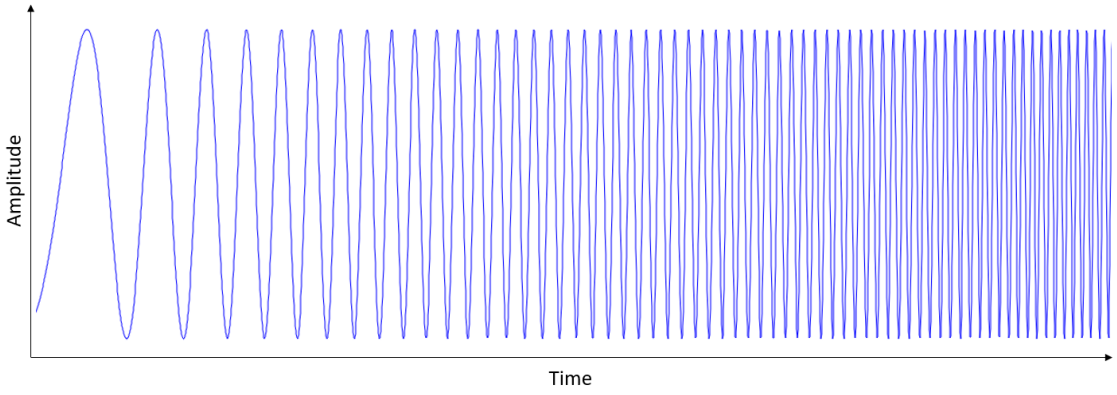

Figure 11. Typical time-domain waveform of FMCW radar

Figure 12 illustrates typical averaged frequency spectrum of FMCW signals. The spectrum bandwidth is *B*. In Figure 13, there are also other several key parameters about FMCW, which are FMCW period *T*, highest frequency f_{max}, and lowest frequency f_{min}. The impacts of these parameters on target detection will be discussed.

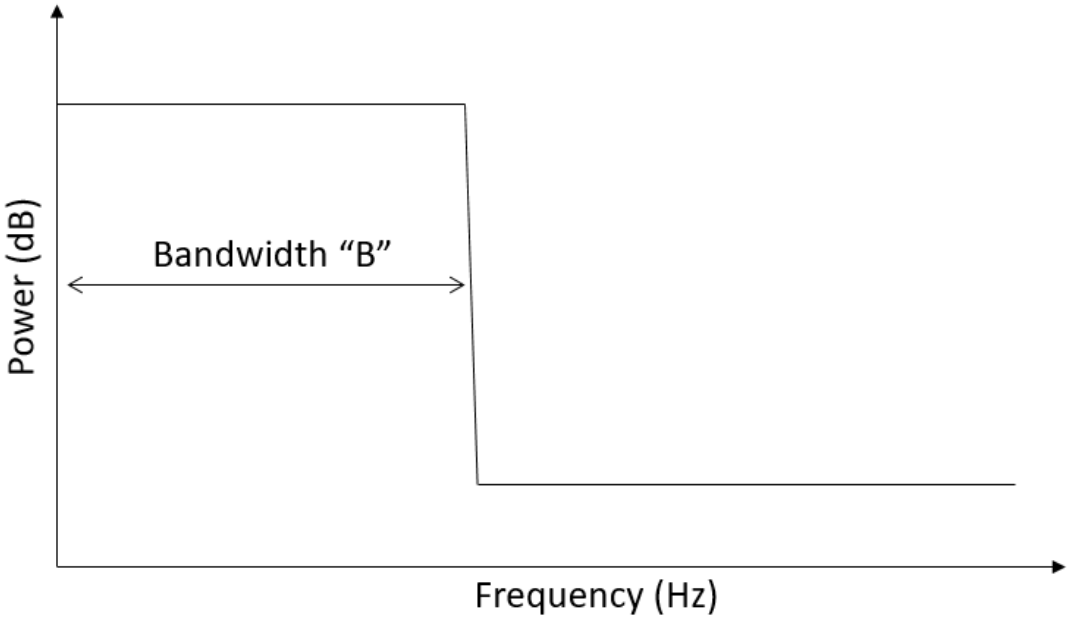

Figure 12. Typical frequency- spectrum of FMCW waveform

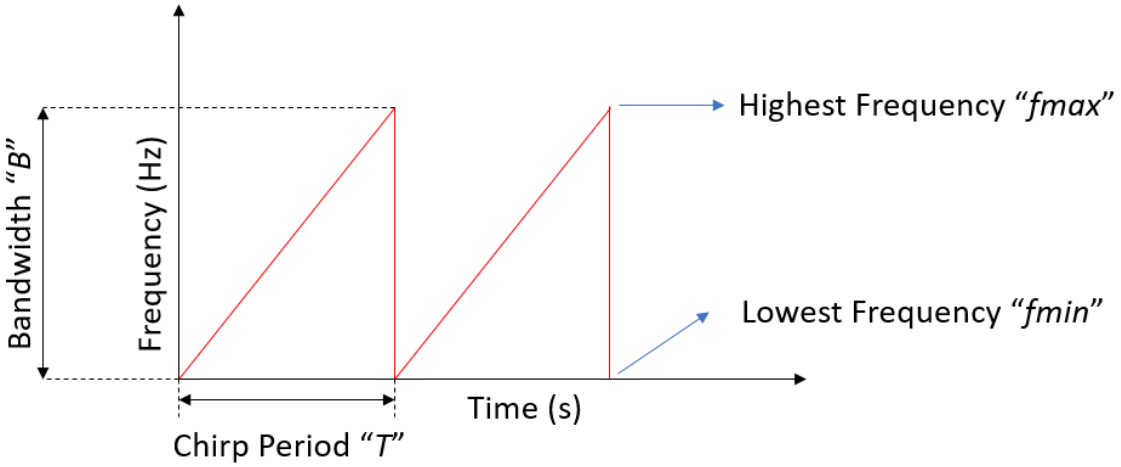

Figure 13. Time-frequency spectrum of FMCW waveform containing multiple sweeps

2.3 Processing Procedures

An FMCW radar has two antennas, one is TX (transmit) antenna, the other is RX (receive) antenna. The TX antenna is incessantly transmitting FMCW signals. The RX antenna is also continuously receiving reflected electromagnetic waves from targets.

After the reflected signal is received, the following basic signal processing procedures are performed.

First, the key system parameters are summarized in Table 1. Let's assume there is only one target presenting, and the antennas and the target are stationary. The distance between antennas and object is *R*, as is shown in Figure 14.

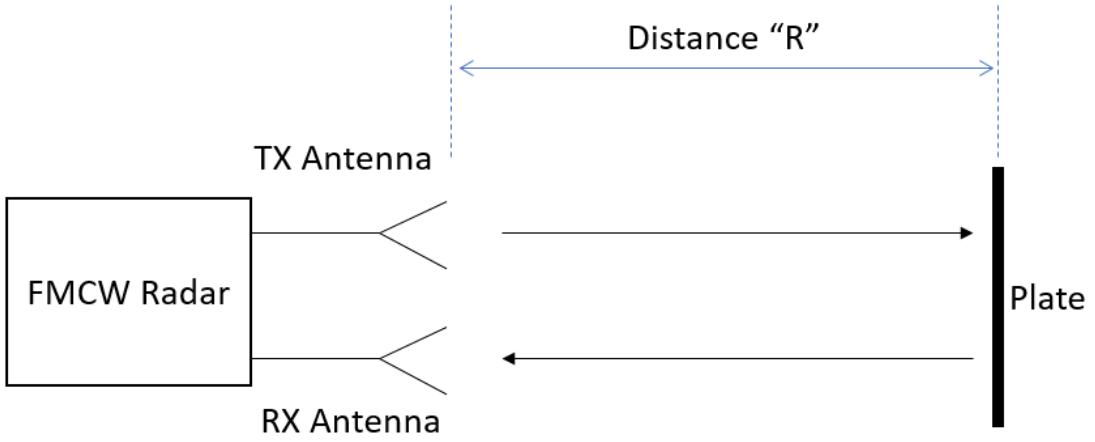

Figure 14. Only one object in front of Radar

Table 1. FMCW Radar Parameters

FMCW bandwidth	*B*
FMCW chirp period	*T*
RX signal time delay	*t*
Frequency difference between TX and RX signal	*f*

The second step is “comparing” the TX signal and the RX signal. Since there is only one target, then Figure 15 shows the TX signal and RX signal in the Frequency - Time plot. The RX signal and the TX signal are totally identical in shape. The only difference is the RX signal is shifted by time *t*. Because the linear frequency change in TX is a function of time, the delayed RX signal is received at a different frequency. Therefore, the frequency difference, $f = f_{TX} - f_{RX}$, can be used to estimate *t*.

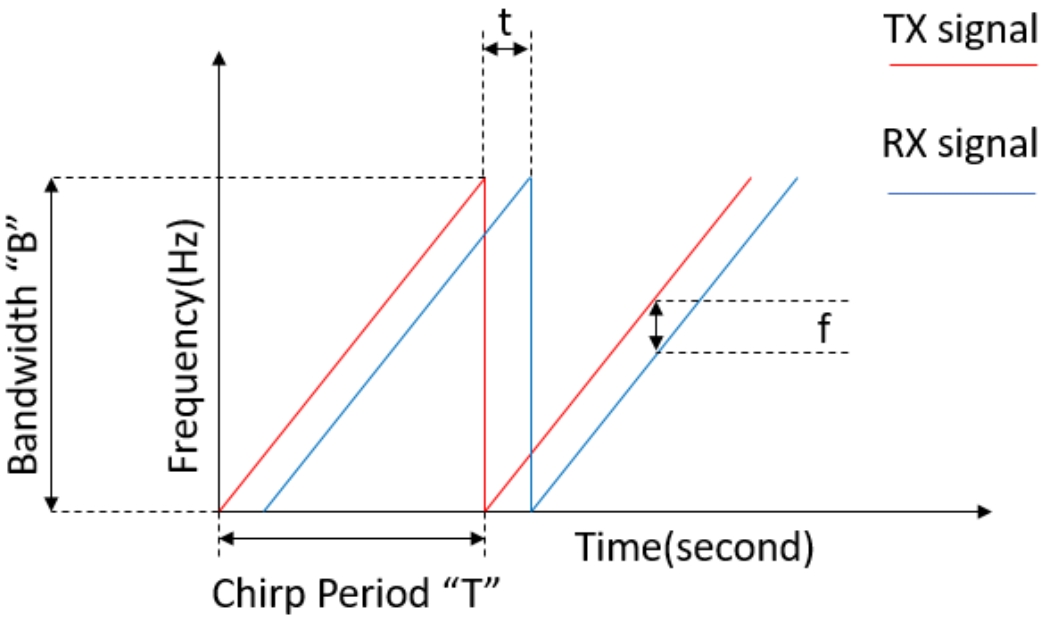

Figure 15. FMCW TX and RX signal frequency-time plot

The third step is estimating target range *R*. The object range can be extracted from the RX signal time delay *t*. The thing is how to extract *t* from other parameters. Figure 15 shows that *t* is in proportion to *f*.

$$\frac{t}{f} = \frac{T}{B} \qquad (1)$$

$$t = \frac{fT}{B} \qquad (2)$$

$$R = \frac{ct}{2} \qquad (3)$$

The speed of light is *c*. From formula 2 and 3, the object range *R* can be estimated, as in Eq. (4):

$$R = \frac{cfT}{2B} \qquad (4)$$

The values of parameters *c*, *T*, *B* are all given; only *f* is unknown. So as long as one gets the *f* value, the target range can be found.

$$f = TX\ frequency - RX\ frequency \qquad (5)$$

A mixer is usually used as the device for correlating transmit reference and receive signals [9]. A mixer has three ports, two input ports and one output port. A mixer multiplies two signals (functions of time in this case) together, then outputs a new signal which is the mixed signal, as shown in Eq. (6).

$$\cos(2\pi f_{LO}t) \cdot \cos(2\pi f_{RF}t) = \frac{1}{2}\cos(2\pi(f_{RF} + f_{LO})t) + \frac{1}{2}\cos(2\pi(f_{RF} - f_{LO})t) \quad (6)$$

As in Figure 16, the output signal frequencies are $f_{RF} + f_{LO}$ and $f_{RF} - f_{LO}$. The $f_{RF} + f_{LO}$ signal will be removed by a filter, only $f_{RF} - f_{LO}$ will be kept.

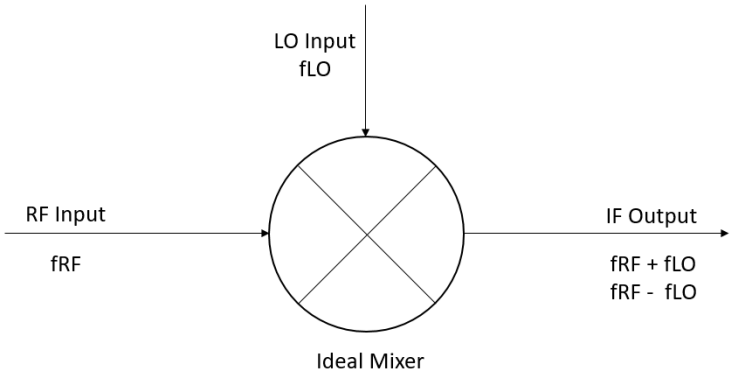

Figure 16. Ideal mixer [9]

The target range value, *R*, can be computed once *f* is known.

2.4 System Simulation and Evaluation

We first performed a series of simulations of the FMCW radar sensors for different assumed targets using GNU Radio Companion. GNU Radio Companion [10] is a Python-based, open-source software tool that can be used to design either simulations or hardware processing codes graphically, similar to LabVIEW [11]. The Companion is also independent of different hardware SDR platforms. In this work, GNU Radio Companion is first used to simulate the radar sensor operations (i.e. no hardware is involved).

Figure 17 shows the flow graph of a basic FMCW radar sensor, and plots the transmitted waveform from a probe in the system.

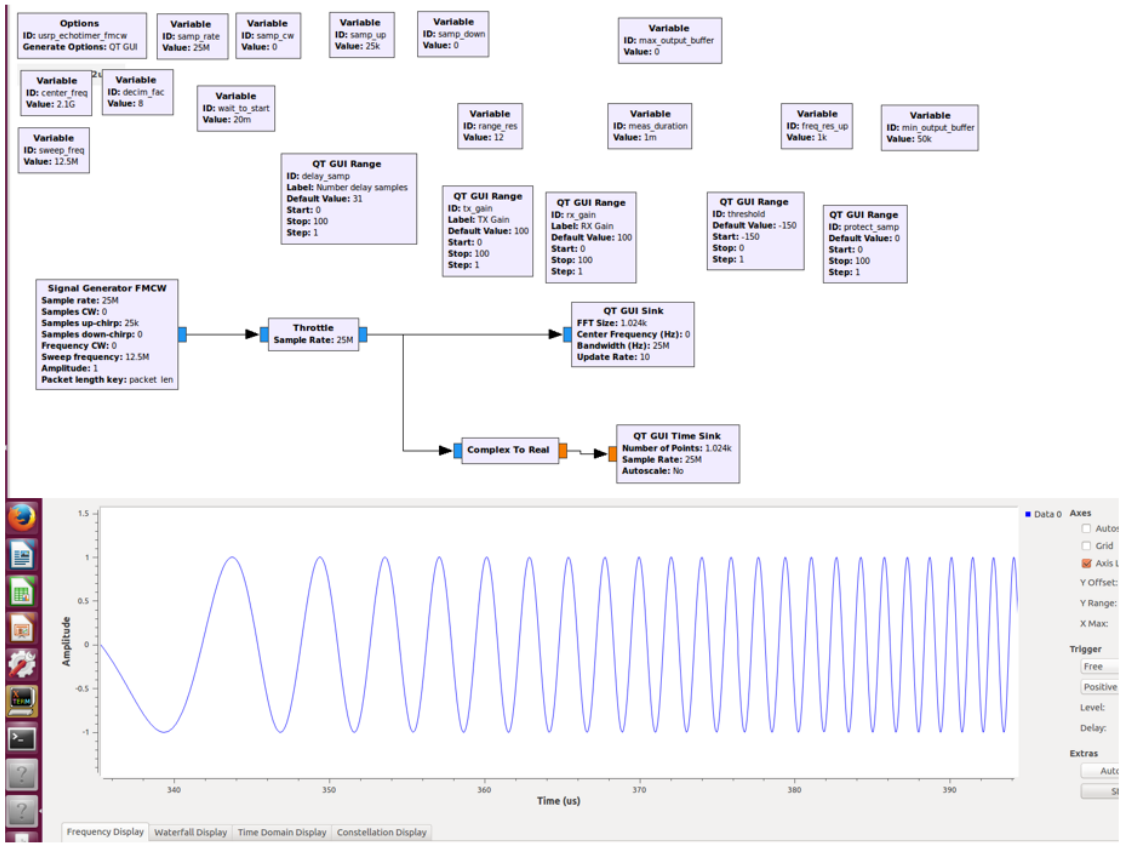

Figure 17. FMCW signal simulation in GNU Radio Companion (B= 12.5 MHz)

In these simulations, due to the massive amount of data and limitation of CPU, the FMCW signal is stored into a data file for offline processing using MATLAB. The processing flowchart is shown in Figure 18.

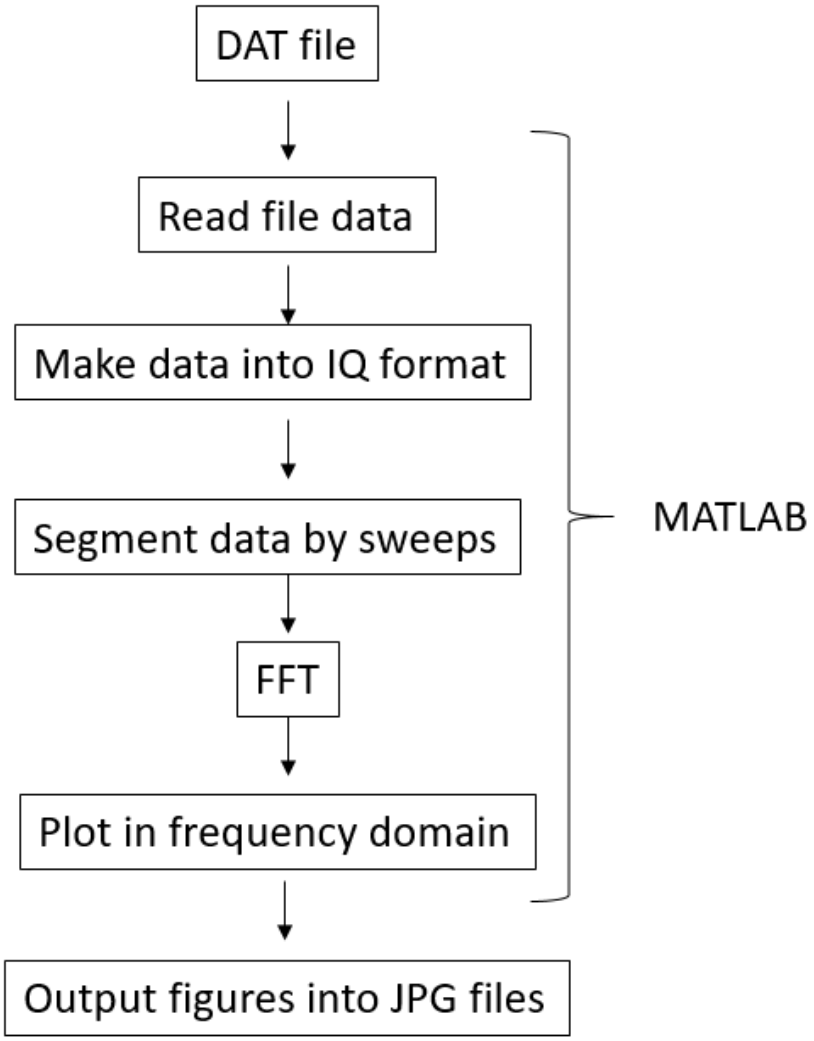

Figure 18. Flowchart of simulation data processing in MATLAB

The spectrum of the FMCW transmit signal in this simulation example is shown in Figure 19. As mentioned before, the spectrum looks like a "gate" whose width is the bandwidth *B*. *B* ranges from 0 Hz to 6 MHz in Figure 19.

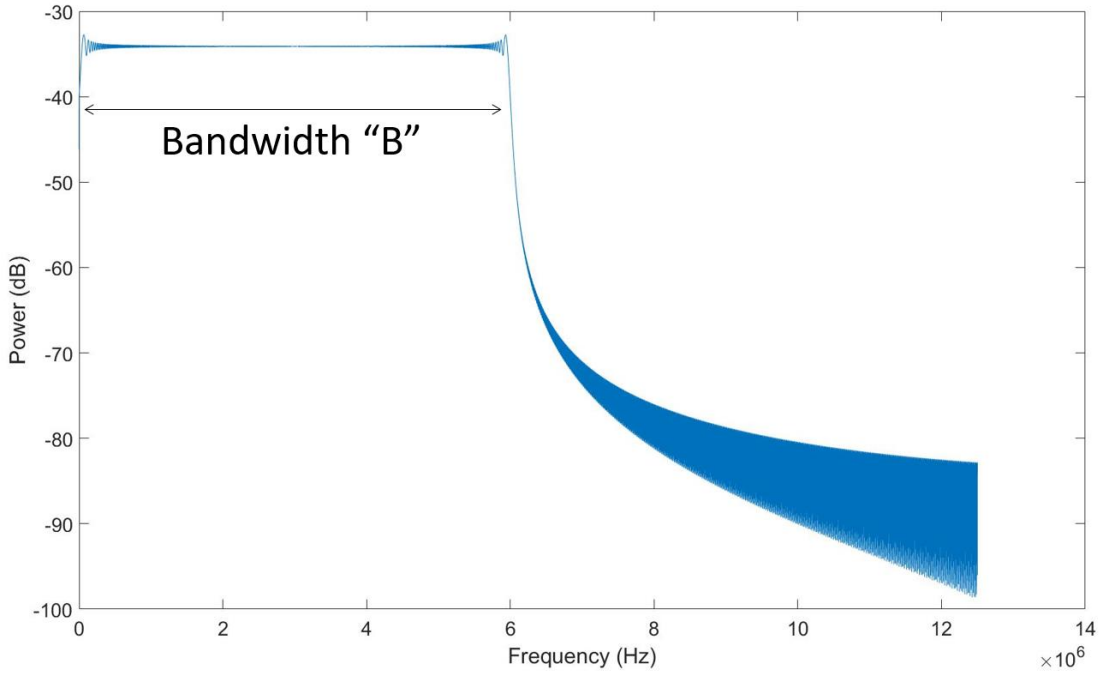

Figure 19. FMCW TX signal spectrum plot

The receive (RX) signal for a simple stationary point target can be simulated by delaying the transmit signal with a certain time. The "delay" block is used here to simulate the RX signal, as in Figure 20.

In this one-target simulation, the FMCW chirp period *T* is 1ms and the bandwidth *B* is 12.5MHz. During 1ms time, the FMCW generator outputs 25 kilo samples. Figure 20 delays 10 kilo samples, which means the time delay *t* is *0.4T*.

$$t = \frac{10K}{25K}T = 0.4\,T$$

According to Eq. (1),

$$f = \frac{tB}{T} = \frac{0.4TB}{T} = 0.4B = 0.4\times12.5 = 5MHz$$

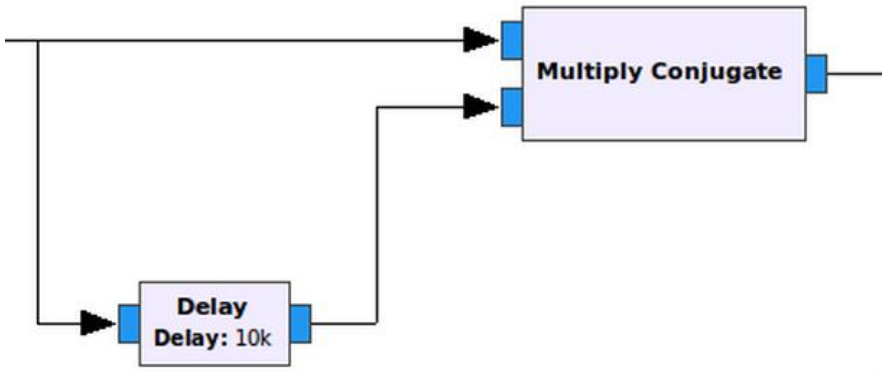

Figure 20. Simulating one target

The target range profile is obtained by performing FFT on the correlator (mixer) output. An example result is shown in Figure 21. The spectral peak is the target signature and has a value of 5 MHz, which matches the calculation. The next procedure is to convert the frequency-power plot into a range-power plot. According to Eq. (4), the Figure 21 *x*-axis frequency scale can be converted to range scale, as shown in Figure 22. In this case, the peak located at 5 MHz is translated to a true target distance of 60 km in Figure 22.

$$R = \frac{cfT}{2B} = \frac{c\times5MHz\times T}{2B} = 60\ kilo\ meters$$

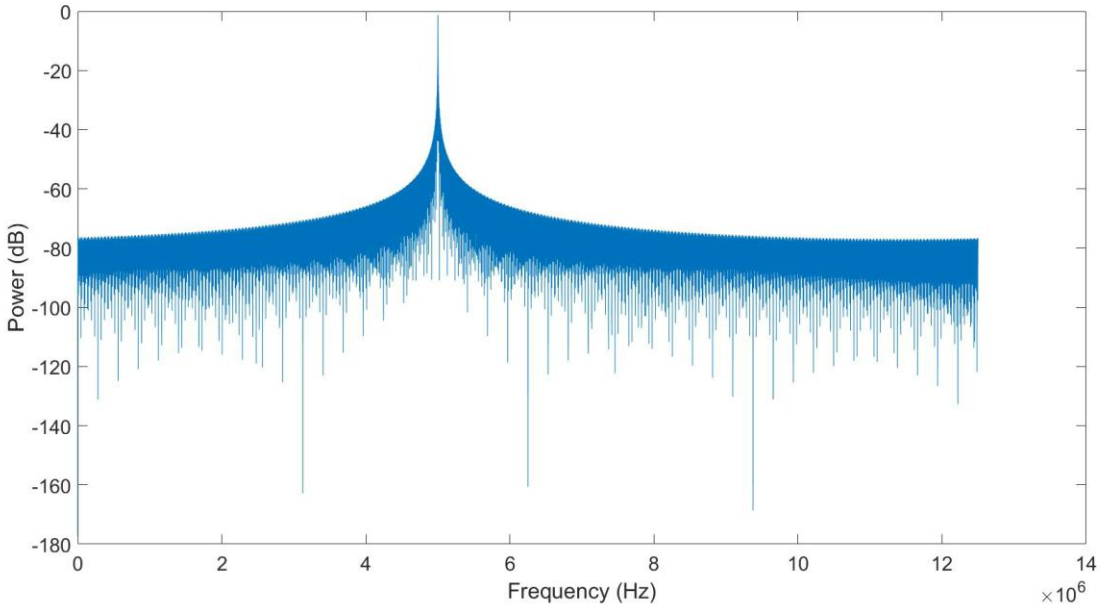

Figure 21. Frequency-domain plot

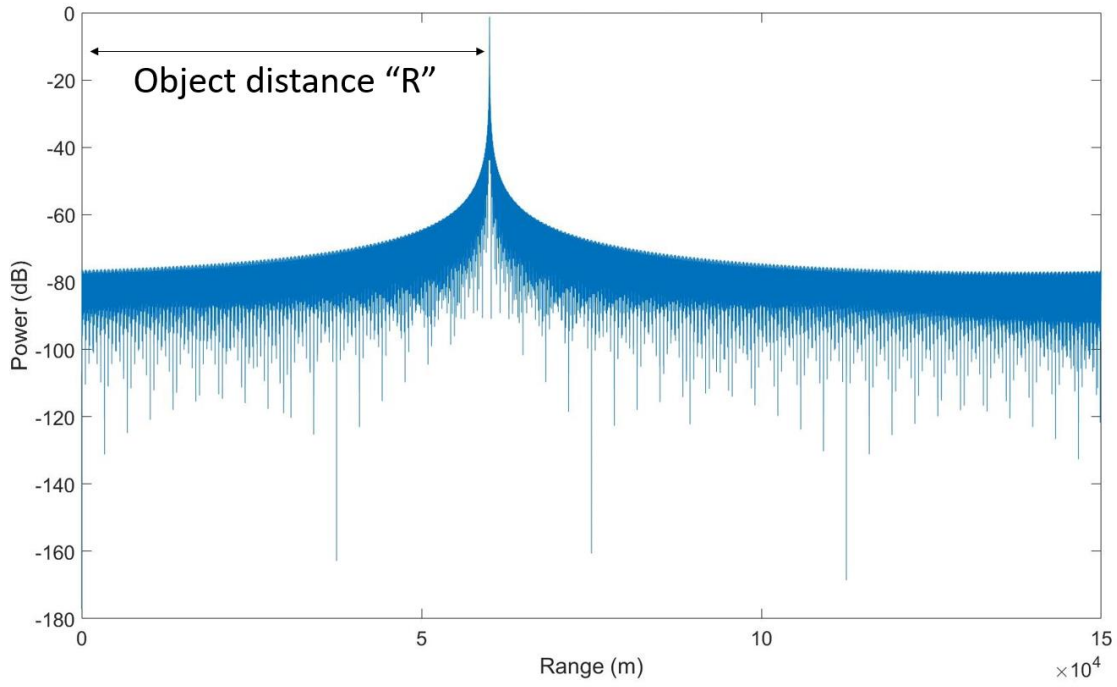

Figure 22. Typical range profile of a single point target (simulated, noise-free)

Multiple targets can be simulated by adding more “delay’ blocks and these values of three “delay” blocks are set small to simulate close targets, as shown in Figure 23.

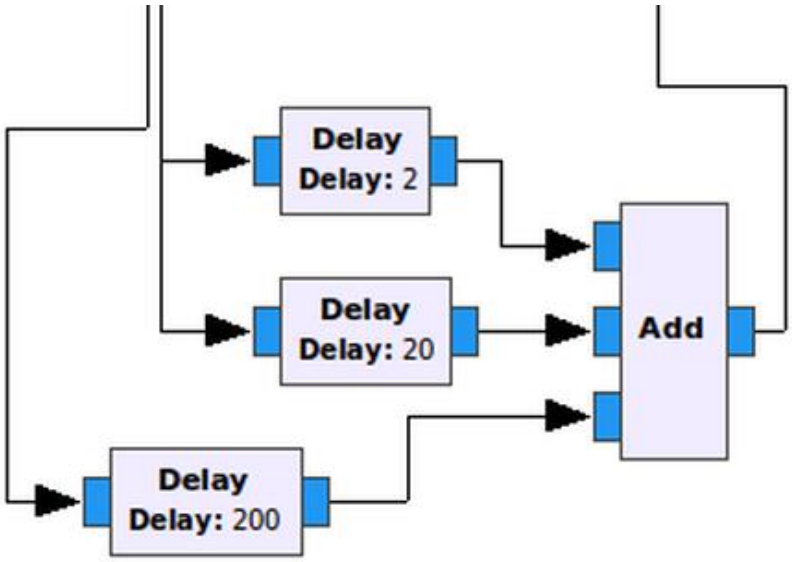

Figure 23. 3 Delay-block in GNU Radio Companion for simulating radar returns of 3 targets

After executing the simulation program again, a new DAT file is generated. Then the file is moved to a PC to be processed in MATLAB. After MATLAB processing, the range-power plot is generated, as shown in Figure 24. At first glance, the three targets are hardly discernable because the peaks are at the very left side of the plot. After zooming the plot, 3 targets can be seen, as shown in Figure 25. From left to right, the ranges of the targets are 12-meters, 120-meters and 1200-meters.

According to Figure 20 - Figure 22, we know how the “delay” block value 10k is related to the range 60km in math. Therefore, the range values 12-meters, 120-meters and 1200-meters match the “delay” block values 2, 20 and 200.

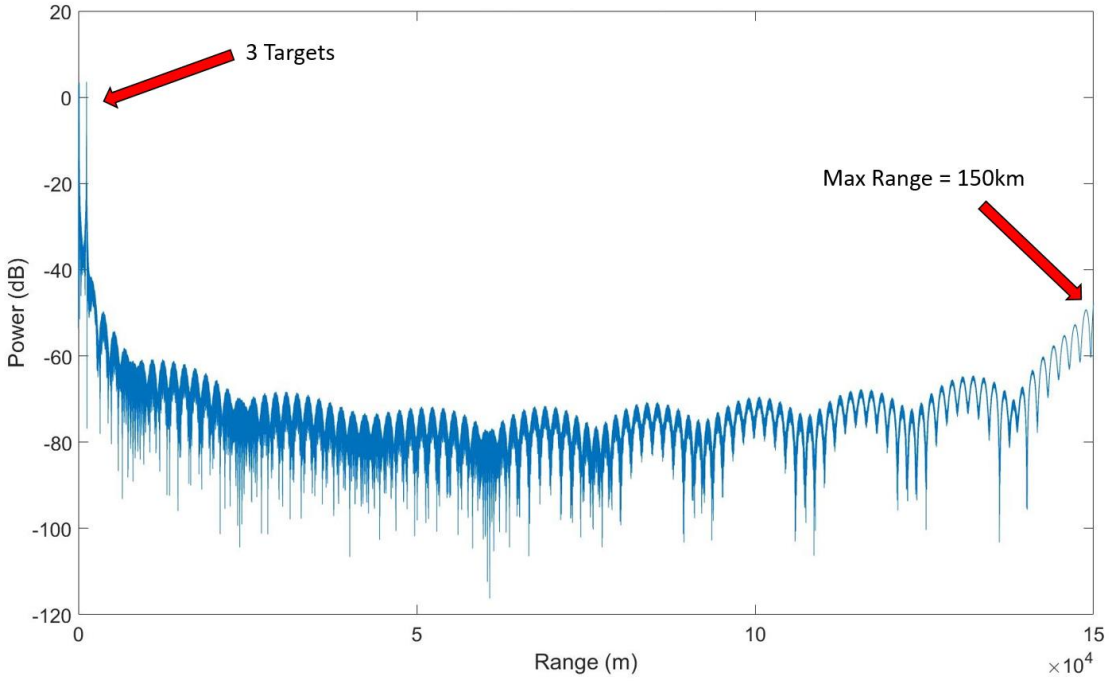

Figure 24. Simulation target range-power plot

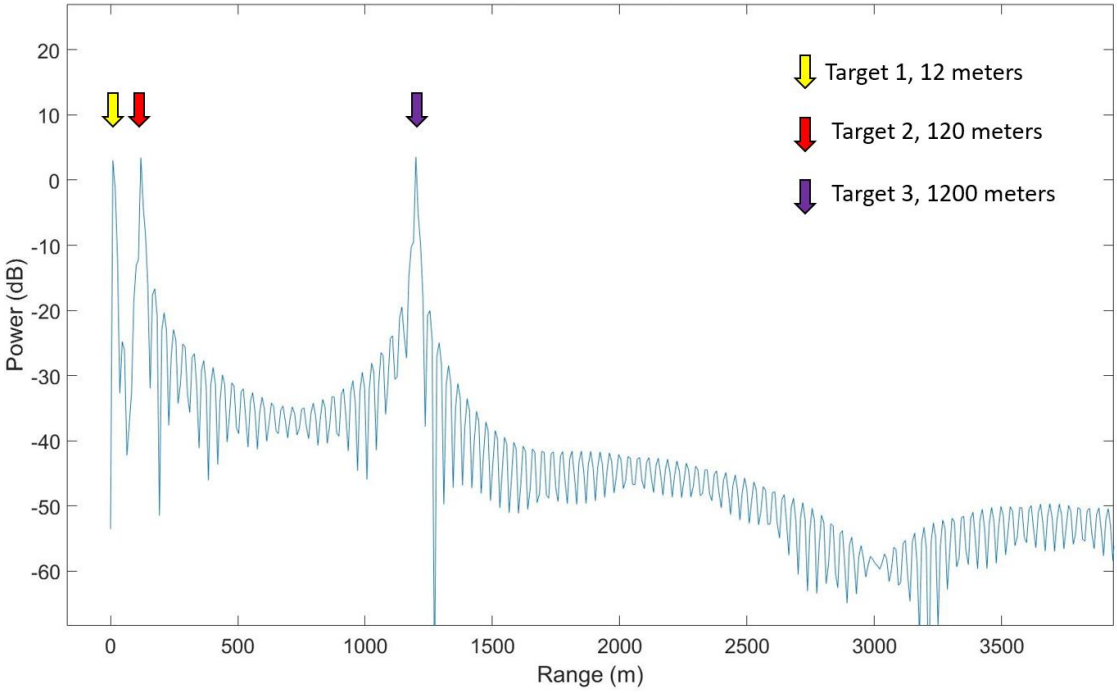

Figure 25. 3 Simulation targets zoom showed in range-power plot

To understand what parameters of FMCW Radar can affect the maximal non-ambiguous range, the following relation can be derived from Eq. (4):

$$R_{max} = \frac{c f_{max} T}{2B} \qquad (7)$$

According to the sampling theorem:

$$f_{max} = \frac{F_s}{2} \qquad (8)$$

Fs is the A/D converter sample rate. By combining equations (7) and (8), we have

$$R_{max} = \frac{c F_s T}{4B} \qquad (9)$$

According to Eq. (9), 3 parameters can affect the max non-ambiguous range. Note the physical meaning of f_{max} is the max frequency difference between the TX signal and the RX signal, which cannot exceed bandwidth *B*. Eq. (8) could be rewritten as:

$$f_{max} = \begin{cases} \frac{F_s}{2}, & F_s < 2B \\ B, & F_s \geq 2B \end{cases} \qquad (10)$$

And Eq. (9) can be re-written as:

$$R_{max} = \begin{cases} \frac{c F_s T}{4B}, & F_s < 2B \\ \frac{cT}{2}, & F_s \geq 2B \end{cases} \qquad (11)$$

Another important metric is range resolution. Based on Eq. (4), we can derive:

$$Range\ Resolution = \frac{c f_{resolution} T}{2B} \qquad (12)$$

$$f_{resolution} = \frac{F_s}{N} \qquad (13)$$

Where *N* is the number of samples per sweep.

$$N = F_s \times T \qquad (14)$$

By putting (13) and (14) together, we have

$$f_{resolution} = \frac{1}{T} \qquad (15)$$

By combining Eq. (12) and (15), Eq. (16) shows the range resolution of a FMCW Radar formula,

$$Range\ Resolution = \frac{c}{2B} \qquad (16)$$

From (16), we can conclude that the range of a FMCW Radar is only related to bandwidth, *B*.

Chapter 3: SDR Platforms

With the rapid development of integrated circuits and software in last decades, an increasing number of SDR platforms are available, which provide numerous choices and great convenience. Those platforms have different microprocessors, FPGAs (field programmable gate array), operating frequencies, bandwidths, output power levels, A/D converters, user software, prices, etc. These specifications need to be assessed before implementing the FMCW sensor into one of the platforms.

3.1 STREAM Board and UNITE7002

Lime Microsystems company produces an SDR development kit, including Stream board and UNITE7002 board, as shown in Figure 27. According to the user guides [12, 13], more details of this kit are described next.

The Stream board is the base board, and the core of the Stream board is a FPGA chip. It also has a lot of useful peripheral ports, a micro SD card socket, USB slots, an Ethernet port, etc. The Stream board mainly functions as a processor or controller.

UNITE7002 board is a transceiver board, and the core of the UNITE7002 board is LMS7002M which is a programmable RF chip. Similar to the Stream board, the UNITE7002 has many peripheral ports.

The Stream board and the UNITE7002 board are connected by FMC connector, as seen in Figure 26. The LMS7002M's main specifications are listed below, and based on the specifications it was determined that this kit could meet the requirements of FMCW Radar functions.

Table 2. LMS7002M Main Specifications [14]

Operating Frequency Range	100 kHz to 3800 MHz
RF Modulation Bandwidth	60 MHz through digital interface
	160 MHz through analog interface
Maximum RF Output Power	0 dBm Continuous Wave

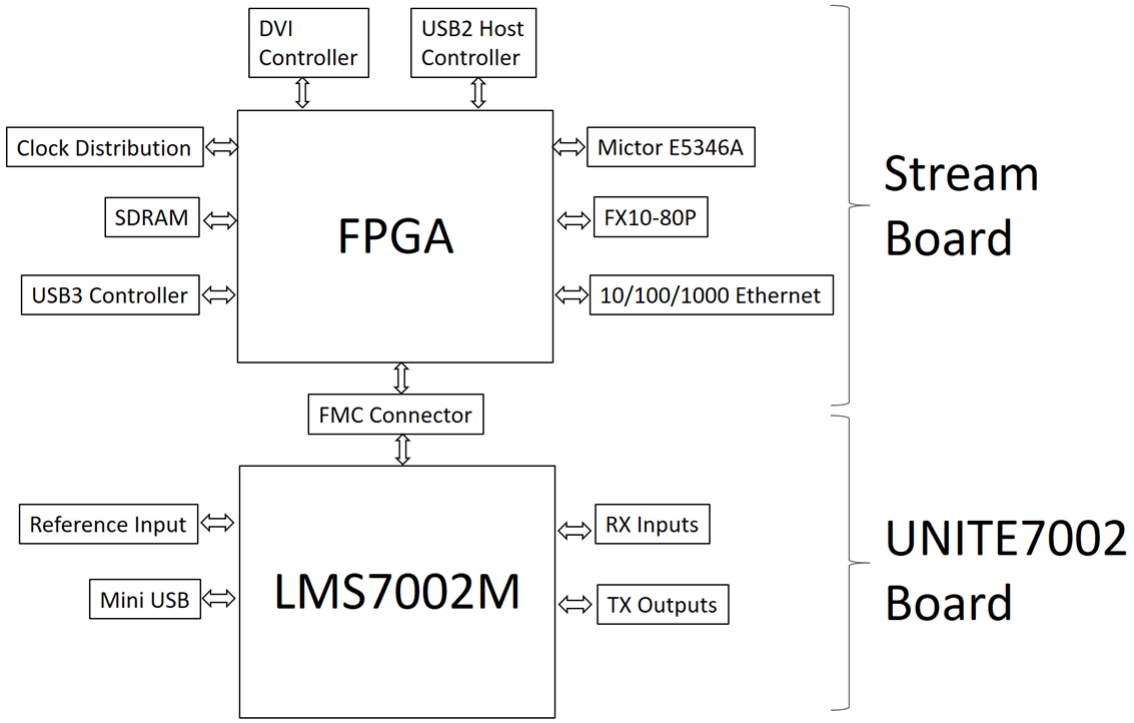

Figure 26. Stream & UNITE7002 boards system [12, 13]

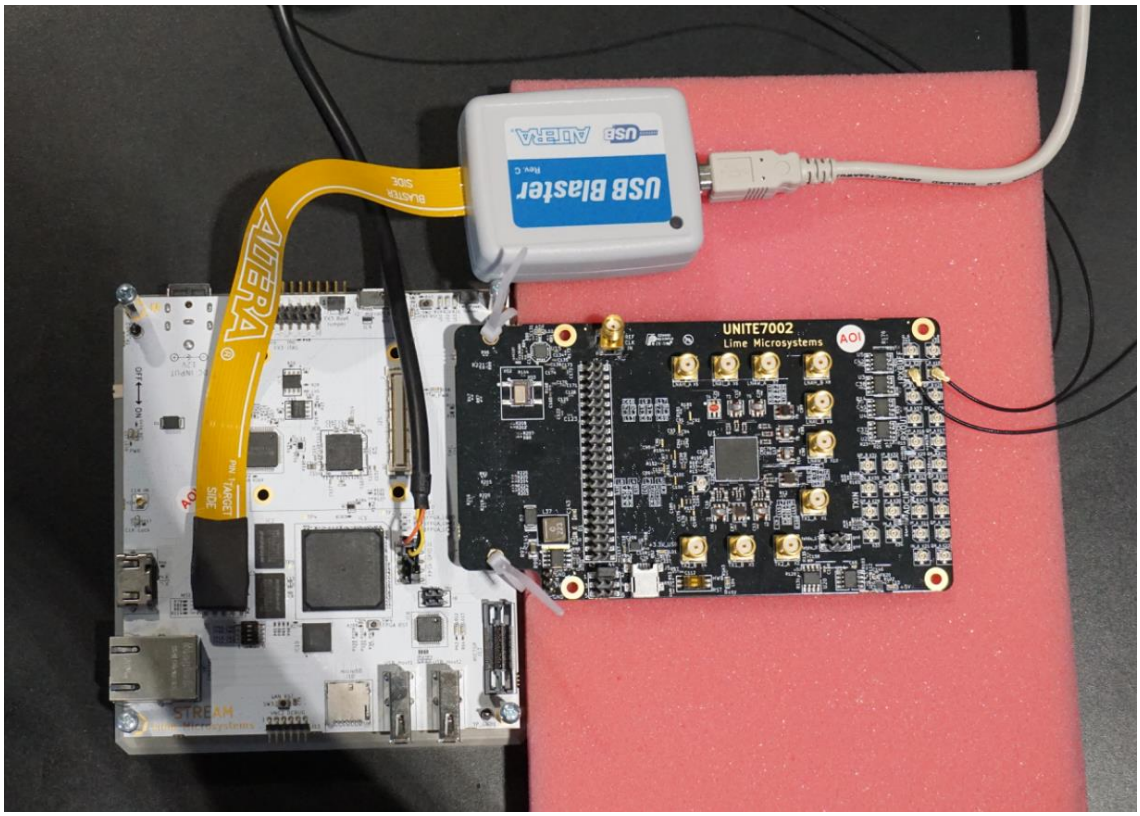

Figure 27. The Stream board (left) and the UNITE7002 board (right)

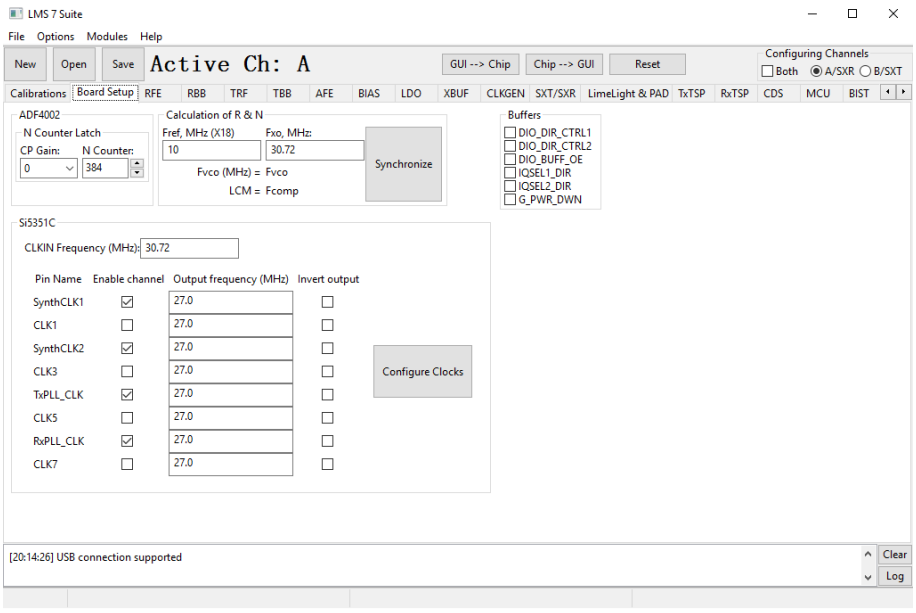

Figure 28. Lime Suite GUI for STREAM Board & UNITE7002

There are three ways to program this kit to make it function as a FMCW Radar. Firstly, Lime Microsystems provides a GUI called “Lime Suite GUI” for this kit, as shown in Figure 28. This GUI helps the user access configuration registers in the kit. This GUI only provides settings for basic parameters, so it cannot support complex radar functions. This method does not work for radar. Secondly, the Stream board FPGA can be programmed. There are two main programming languages for FPGA: one is Verilog, and the other is VHDL. If we try to program the FPGA to make this kit function as a radar, it would require significant effort; for example FMCW baseband generation, setting LMS7002M chip parameters, TX and RX center frequency, bandwidth, signal data storage, peripherals ports, and etc. This method is not an appropriate choice given the constraints of this work. Thirdly, by installing Linux OS into this kit and making it function as a radar under Linux OS. Another user guide [15] gives a Linux solution for Stream board. The basic concept of this idea is to use the Linux OS to make the kit a FMCW radar. As in Figure 30, programming with the OS involves an OpenRISC architecture processor, Linux driver development, and the FMCW Radar user application developments. The OpenRISC script realizes a RISC processor on the FPGA. Overall, this method is not advisable because it requires a lot of computer architecture knowledge and Linux OS knowledge.

```
C:\Users\Jiaxi Zhu>cd C:\Program Files\GNU ARM Eclipse\OpenOCD\0.10.0-201601101000-dev\bin

C:\Program Files\GNU ARM Eclipse\OpenOCD\0.10.0-201601101000-dev\bin>Openocd -f interface/alt
GNU ARM Eclipse 64-bits Open On-Chip Debugger 0.10.0-dev-00287-g85cec24-dirty (2016-01-10-10:
Licensed under GNU GPL v2
For bug reports, read
        http://openocd.org/doc/doxygen/bugs.html
Warn : Adapter driver 'usb_blaster' did not declare which transports it allows; assuming lega
Info : only one transport option; autoselect 'jtag'
Info : vjtag tap selected
Info : adv debug unit selected
Info : Option 7 is passed to adv debug unit
```

Figure 29. Preparing Linux for Stream Board

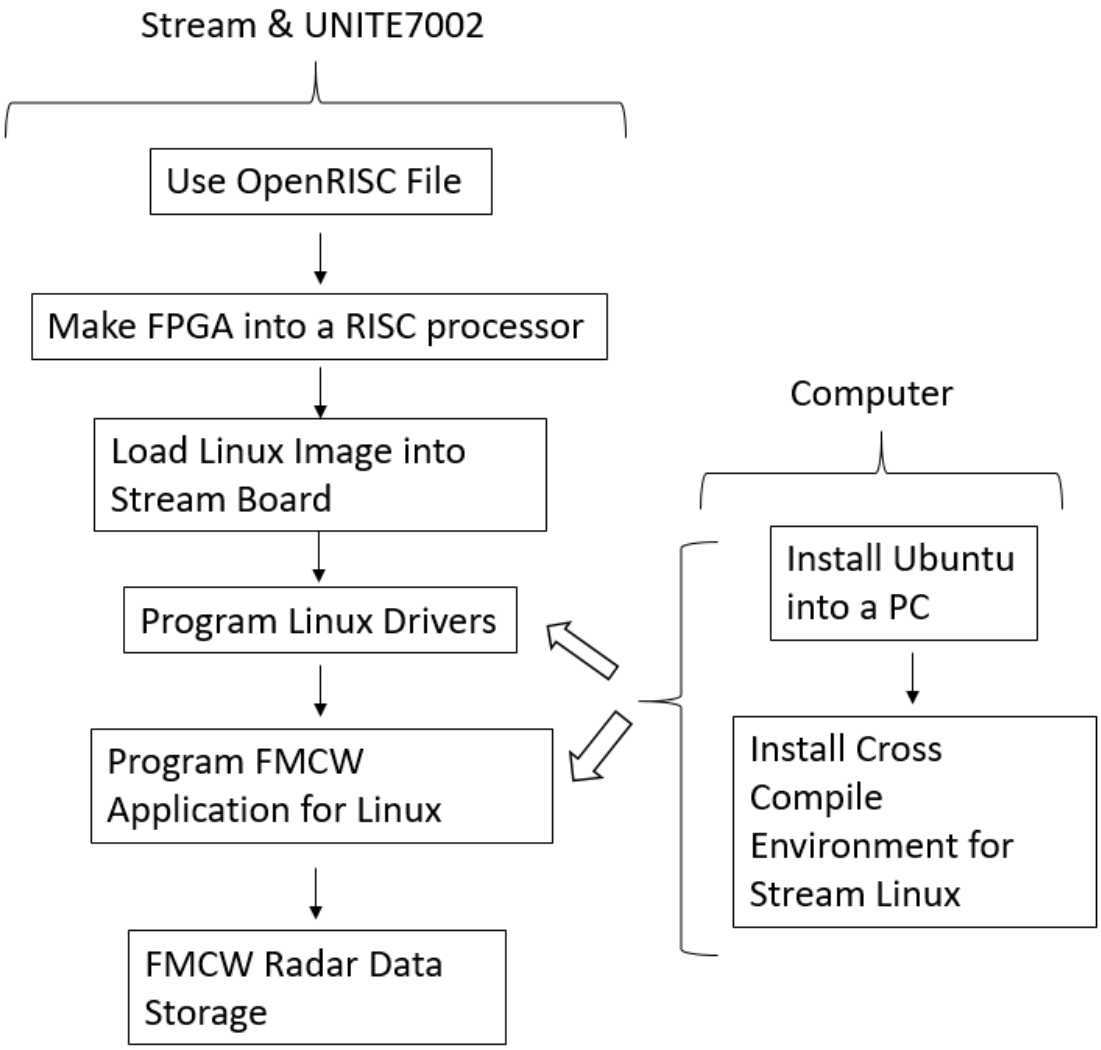

Figure 30. Linux Development in Stream & UNITE7002 for FMCW Radar [15]

3.2 MicroZed Board and MicroZed FMC Carrier

Avnet Inc. was also introduced a development kit for SDR. It has two parts, one of which is the MicroZed board, and the other is the MicroZed FMC Carrier Card. The MicroZed board is mounted on the FMC Carrier. This kit does not include a transceiver board, but it has several sockets for a transceiver, for instance, the FMC connector. Figure 32 is the block diagram based on the Avnet user guide [16]. The core of this kit is the Zynq 7000 chip. The Zynq 7000 chip has an ARM CPU and an FPGA [17]. The MicroZed board also has Linux support [16]. This product is like the Stream board and UNITE7002, and would therefore require the same programming. As a result, this product is not suggested.

Figure 31. The MicroZed Board (top) and the MicroZed FMC Carrier (bottom)

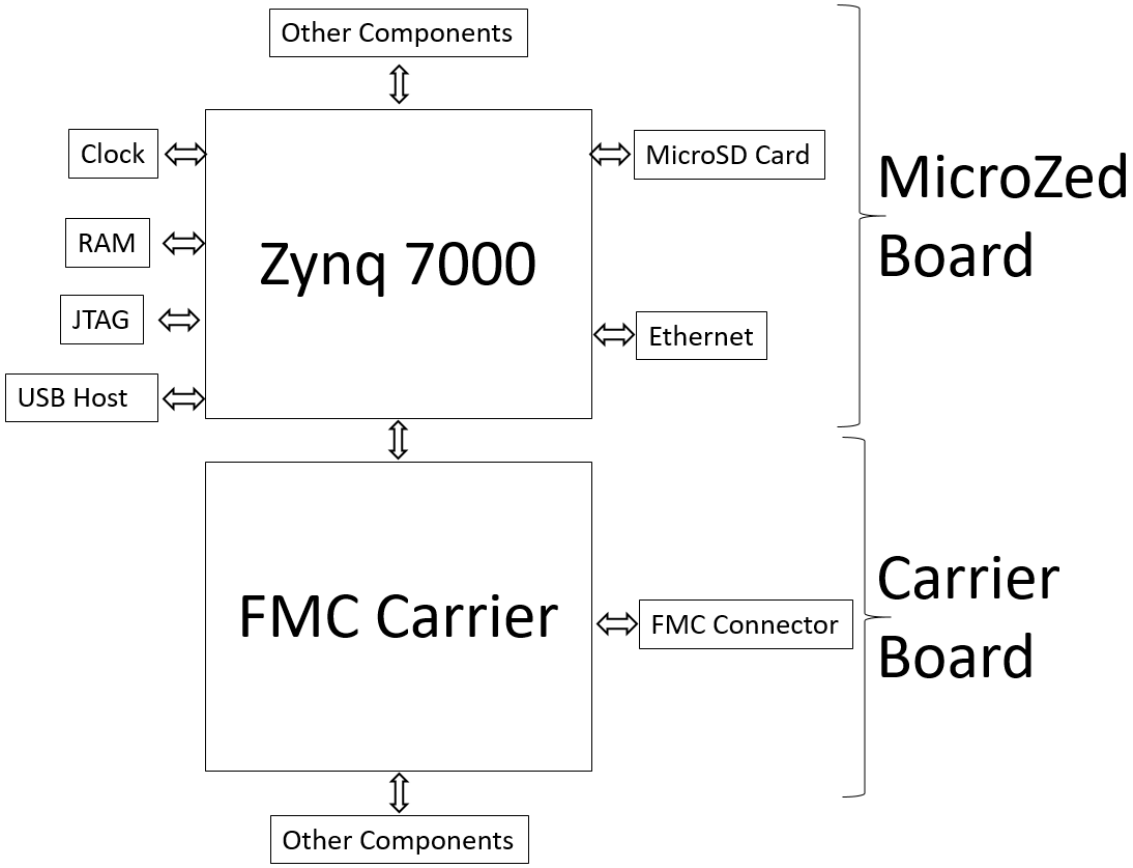

Figure 32. MicroZed kit system diagram [16, 18]

3.3 USRP E310

The USRP E310 board is from Ettus Research. The E310 is a hand-size SDR platform which makes the board portable. According to the E310 datasheet [19], it has many good features, like a transceiver inside which covers the 70 MHz to 6 GHz operating frequency range. It also supports several different SDR programming languages, for example GNU Radio, C/C++, Python, and more. Furthermore, Ettus Research provides drivers to let users interface with the E310.

Figure 33. USRP E310 board

Table 3. E310 Main Specifications [19]

Frequency Range	70 MHz to 6 GHz
RF Ports	2 RX, 2 TX
Bandwidth	Up to 56 MHz
Output Power	>10 dBm
ADC Sampling Rate	61.44 MS/s Max

Table 3 shows the E310's capability. But when using the E310 to do experiments, due to reasons such as computer CPU speed limitation, Ethernet streaming speed, and GNU Radio Companion efficiency, the E310 cannot support a high sampling rate, as shown in Figure 34. As a result, a high-performance alternative is needed.

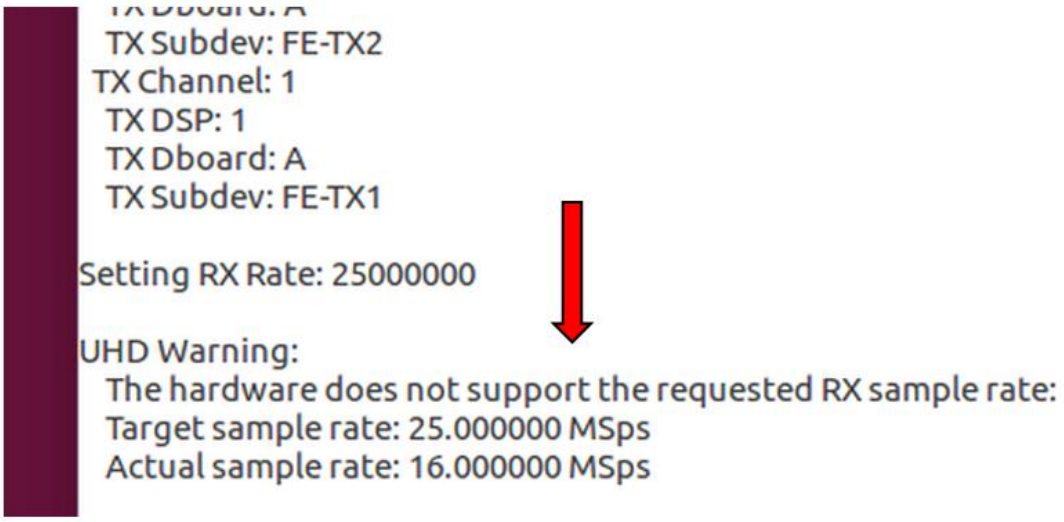

Figure 34. E310 cannot support high sampling rate

3.4 USRP N210 Board

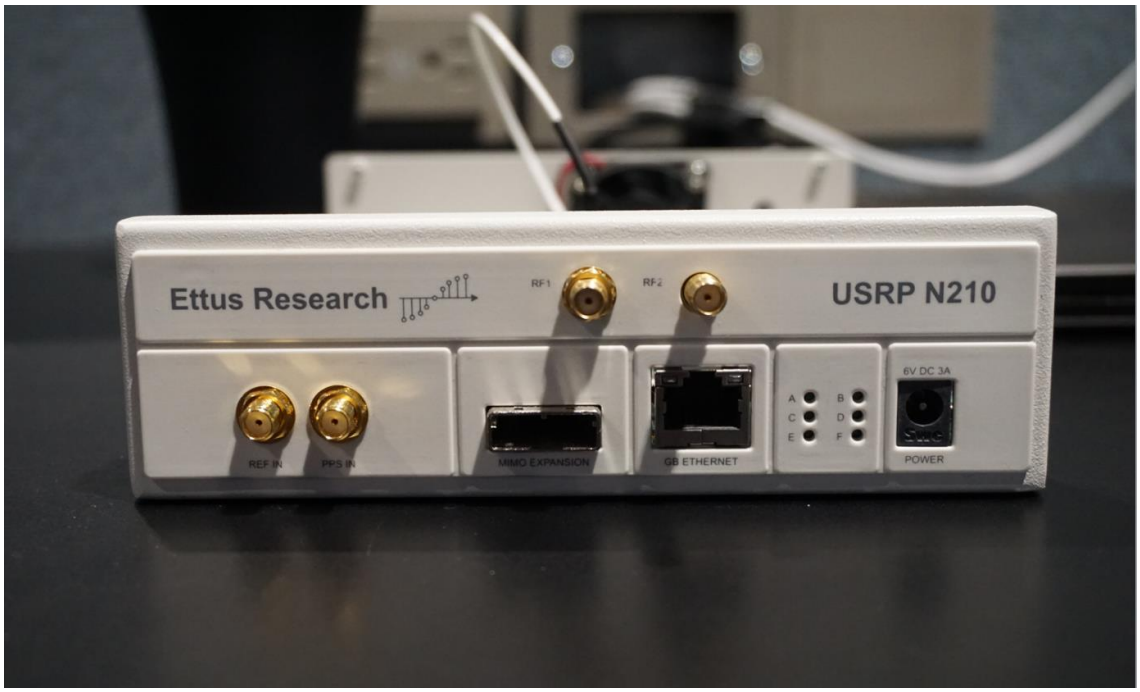

Figure 35. USRP N210 board

The USRP N210 board is also from Ettus Research. The N210 has better performance than the USRP E310, and the ADC sampling rate is up to 100MS/s [19, 20]. The N210 is a base board, and it does not include any transceiver. But it has a transceiver socket which is compatible with some transceiver cards. Ettus has introduced two transceiver cards for the N210, “XCVR2450” and “WBX”.

According to the XCVR2450’s product website [21], the transceiver device covers the frequency range of 2.4 GHz - 2.5 GHz or 4.9 GHz - 6.0 GHz. However, the RX port and TX port of the XCVR2450 cannot work simultaneously, so it is impossible to make it into an FMCW Radar.

Figure 36. XCVR2450 transceiver board for USRP N210 Radios

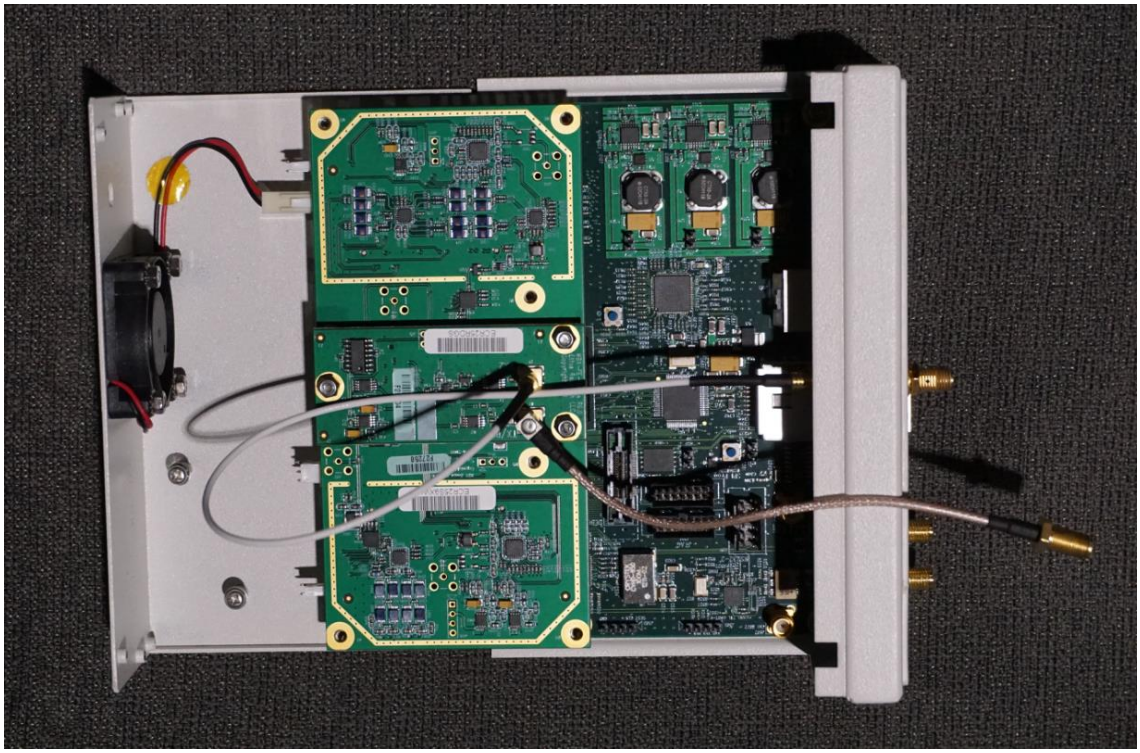

Figure 37. N210 and WBX Board

Figure 37 shows a picture of the WBX mounted onto the N210 board. According to the WBX product website [22], the WBX card supports double-way mode, which means the TX port and RX port can work at the same time. This thesis uses the N210 and WBX for the experiments.

Table 4. WBX Specifications [22]

Frequency Range	50 MHz to 2.2 GHz
Max TX Power	50 MHz to 1.4 GHz 18-20 dBm
	1.4 GHz to 2.2 GHz 12-28 dBm
Bandwidth	40 MHz

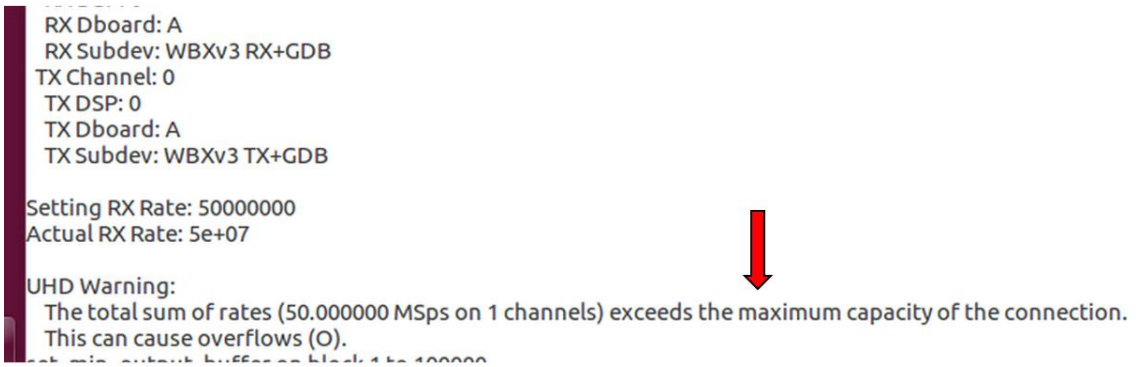

Figure 38. N210 sampling rate capacity

By installing the USRP drivers provided by the Ettus Research, GNU Radio Companion is used to control and communicate with the N210 and WBX. After numerous tests, the N210 and WBX can support a sampling rate of up to 25 MS/s, an FMCW bandwidth of up to 12.5MHz, and a sweep period of 1ms, was achieved.

3.5 QM-RDKIT Board

The QM-RDKIT Radar Demonstration Kit is from the Quonset Microwave company. According to the user manual [23], this kit not only supports FMCW Radar function, but also has other features. For example, it supports USB connection and Bluetooth connection to a host machine, and it can save RAW data for future processing. Windows OS drivers and user GUI (as in Figure 40), including the Android device application, are provided by this kit. Figure 39 is the main part of the kit.

Table 5. QM-RDKIT Main Specifications [23]

Frequency Range	2.4 GHz – 2.5 GHz
Max Bandwidth	100 MHz
ADC Sampling Rate	20,000 Hz
Output Power	1 Watt

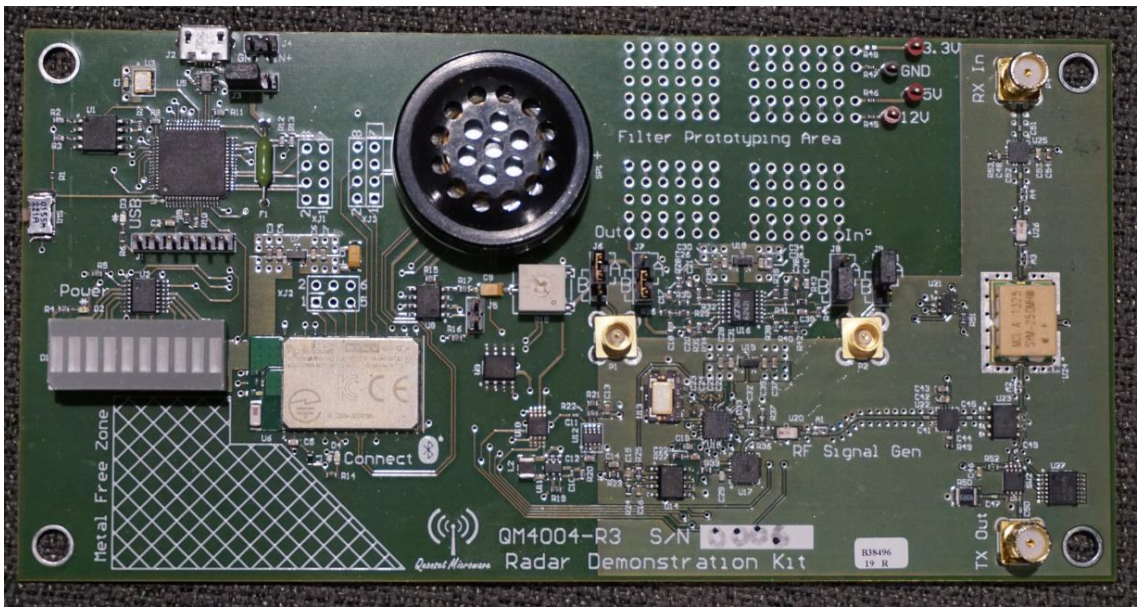

Figure 39. QM-RDKIT board

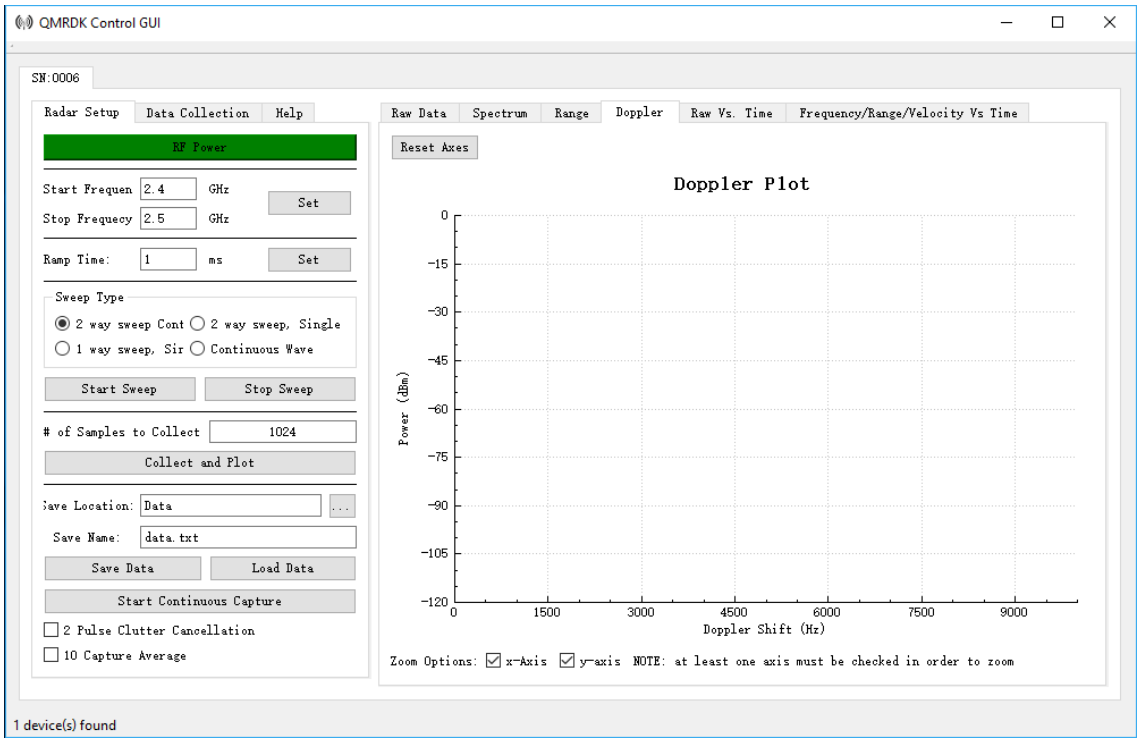

Figure 40. QM-RDKIT Control GUI

Table 5 shows this kit's FMCW maximum bandwidth to be 100 MHz. And it works in the Wi-Fi frequency range, which makes it easy to find economical and compatible antennas and amplifiers. The GUI panel offers great convenience for parameter settings and graph displays. Therefore, the QM-RDKIT kit is recommended.

3.6 Conclusion

To support the experimental study of small drone target observations, we investigated the low-cost SDR hardware platforms available on the market, and compared their performance. Both the N210 kit and the QM-RDKIT kit have suitable operating frequency, bandwidth, sampling rate, uncomplicated programing task, and friendly software support. Therefore, both the N210 kit and QM-RDKIT kit will be used in the following experiments.

Chapter 4: Radar Sensor Experiment

4.1 Experiment Preparation

In addition to the main components of the FMCW radar, discussed in Chapter three, the FMCW radar sensor requires the following two important components for operation: Antenna and Transmit Power Amplifier.

The QM-RDKIT operates in the 2.4 GHz frequency band. The HyperLink HG2418P is a panel antenna for 2.4 GHz use [24]. After a series of tests and comparisons, we selected a pair of HyperLink HG2418P antennas for the QM-RDKIT based system. One is for TX port, the other is for RX port, as shown in Figure 41.

The N210 kit operates at a 2.1 GHz frequency band. The UL-235A-498 horn antenna is suitable for 2.1 GHz [25]. The N210 kit uses a pair of UL-235A-498 horn antennas, as shown in Figure 42.

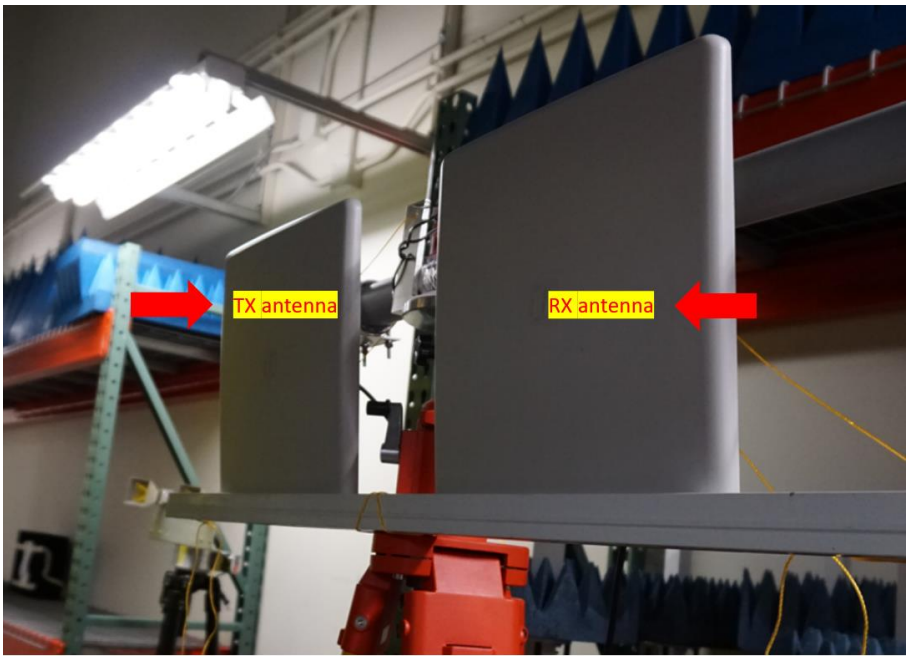

Figure 41. A pair of 2.4 G Hz patched panel antennas for QM-RDKIT

Figure 42. Broadband UL-235A-498 horn antenna for N210-based SDR testbed.

RF transmitting power is an important consideration for radar sensor operations. Due to the output power limitations of the N210 kit and QM-RDKIT [20, 22, 23], we incorporated RF power amplifiers in the transmitter for experiments.

The QM-RDKIT uses a 2.4 GHz carrier frequency (Wi-Fi band). Figure 43 shows multiple Wi-Fi band amplifiers available.

The Mini-Circuits ZVE-2W-272+ is used as a power amplifier for the system based on the N210-kit. The ZVE is a wideband amplifier, shown in Figure 44, operating from 700 MHz to 2700 MHz [26], which covers both the 2.1 GHz operating frequency and the 2.4 GHz band. So, this experiment uses the ZVE-2W-272+ for both the QM-RDKIT and the N210 kit.

Figure 43. 2.4GHz amplifiers

Figure 44. ZVE-2W-272+ (700-2700MHz) amplifier

After acquiring the appropriate hardware, the author made racks with a tripod for the mounting antennas. This concluded the preparation of the hardware for the FMCW radar tests.

The table below lists all important parameters for this experiment.

Table 6. Experimental Parameters Setting [20, 22-26]

	N210 and WBX	QM-RDKIT
Start Frequency	2.1 GHz	2.4 GHz
FMCW Range	0 Hz - 12.5 MHz	0 Hz - 100 MHz
FMCW bandwidth	12.5 MHz	100 MHz
A/D sampling rate	25 MS/s	20 KS/s
Ramp Period	1 millisecond	2 milliseconds
Range Resolution	12 meters	1.5 meters
Maximal Non-ambiguous Range	150 kilometers	30 meters
Data Format	dat	txt
Antenna	Horn Antenna in 2.1GHz	Panel Antenna in 2.4GHz
Amplifier	2 Watt, ZVE-2W-272+	
FMCW Radar Software	GNU Radio Companion in Ubuntu	QMRDK Control GUI in Windows
Signal Processing	MATLAB in Windows	

4.2 QM-RDKIT Configuration and Experiment Results

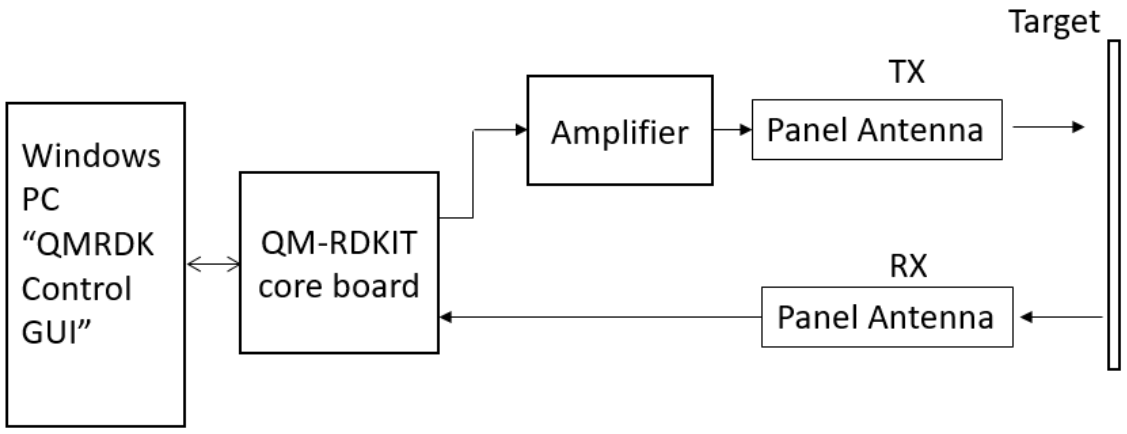

Figure 45. QM-RDKIT system operation

Figure 45 shows the system configuration of the FMCW radar system implementation based on the QM-RDKIT. First, a large reflective foil plate was used as a target because of its significant Radar Cross Section (RCS) [27]. Second, a small drone (Phantom 3) was used as a target. Multiple outdoor experiments were performed, as shown in Figure 46, Figure 47 and Figure 48.

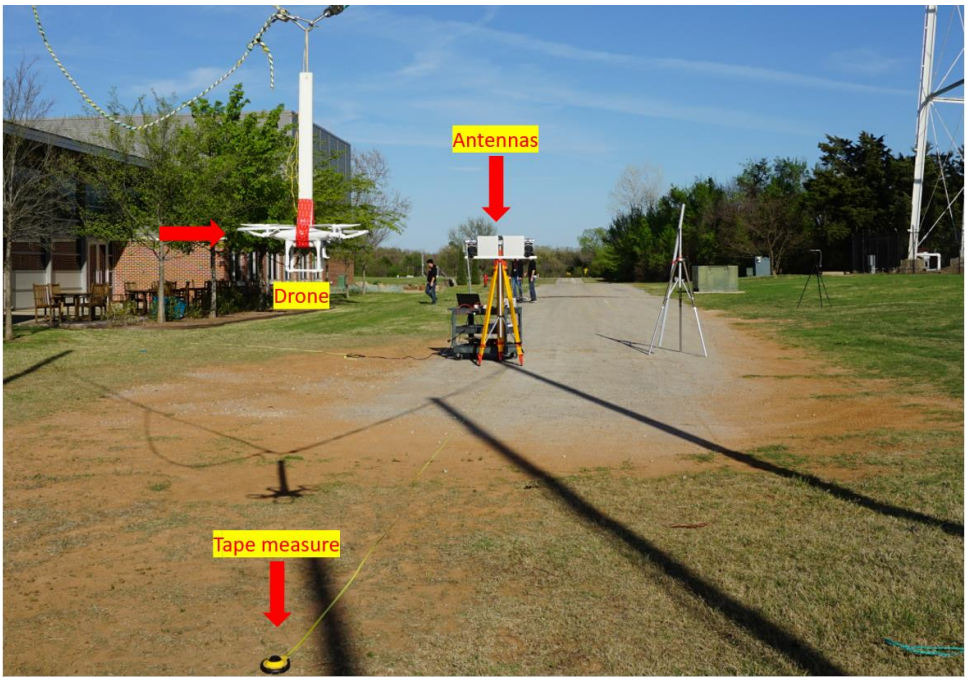

Figure 46. QM-RDKIT out-door test

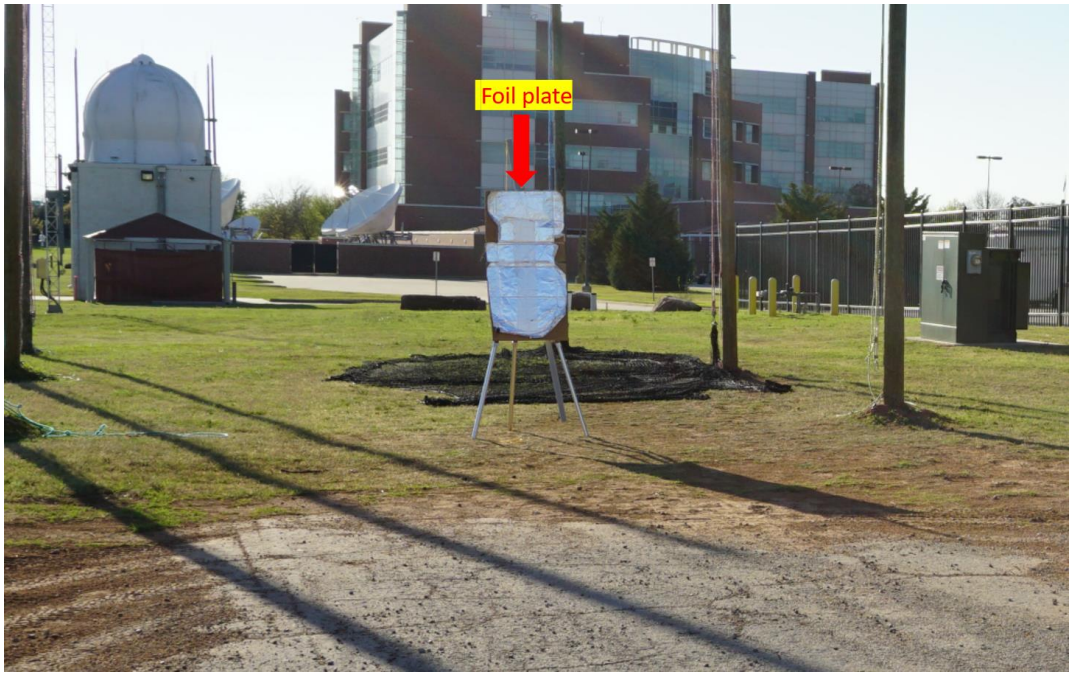

Figure 47. The reflective foil plate target

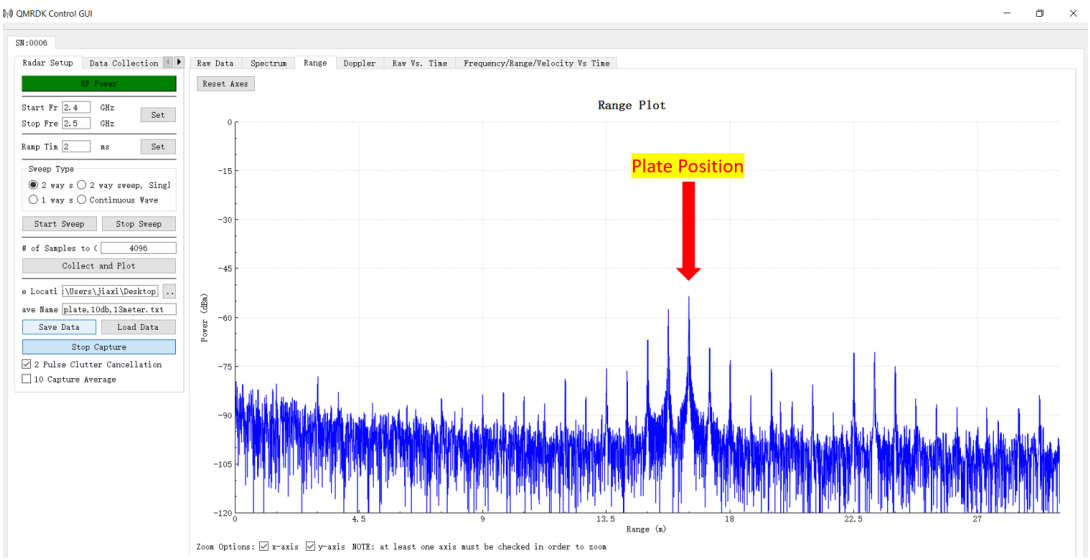

Figure 48. Range-profile plot of a reflective rectangular plate from screen-capture of QM-RDKIT GUI

In the previous experiments, there are 3 sets of data for each experiment: plate data, drone not running data and drone running data. Then the author used the procedures outlined in Chapter 2 to process the RAW data. However, it is hard to see the plate or drone position in all plots, as in Figure 51, Figure 53 and Figure 55.

In order to get good signature graphs, a new processing method is introduced, as in Figure 49. This “subtraction” method needs one more set of data, background data. By this “subtraction” method, plate and drone position can be easily found in the graphs, as in Figure 52, Figure 54 and Figure 56. Furthermore, Figure 56 shows Micro-Doppler signatures around the zero-Doppler frequency. Two reasons can explain the Micro-Doppler effect: one is the spinning blades, and the other is the subtle shake of the drone.

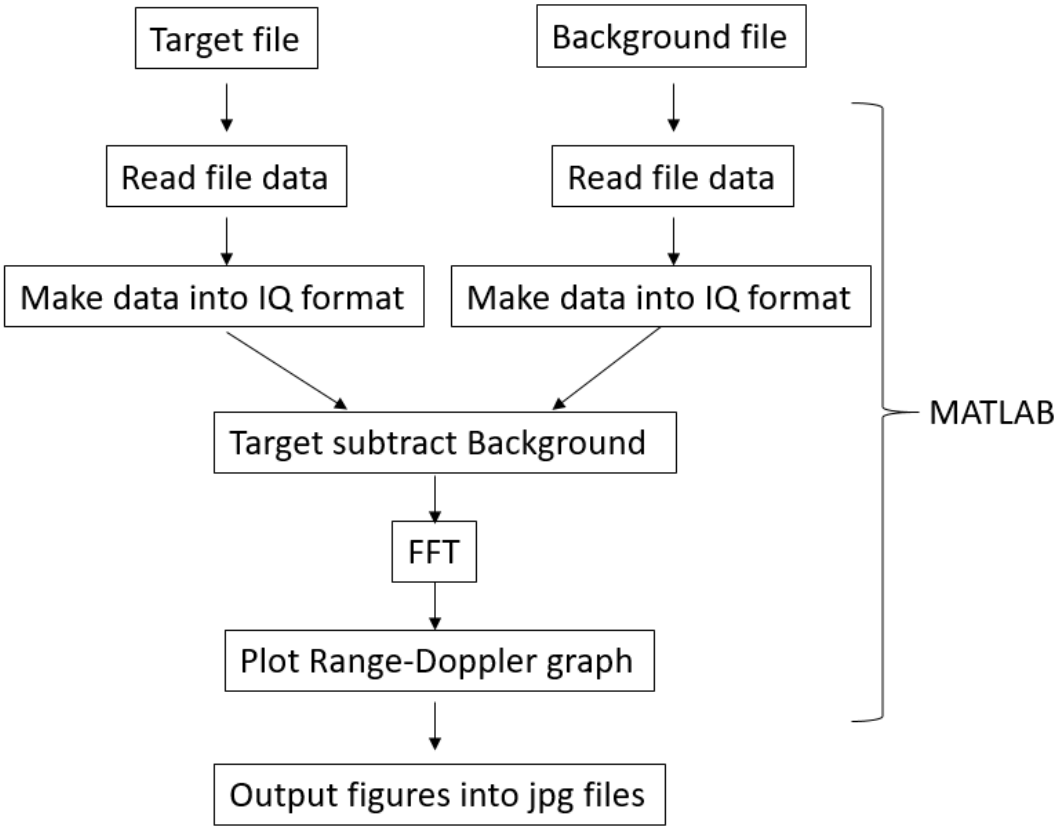

Figure 49. MATLAB subtraction algorithm

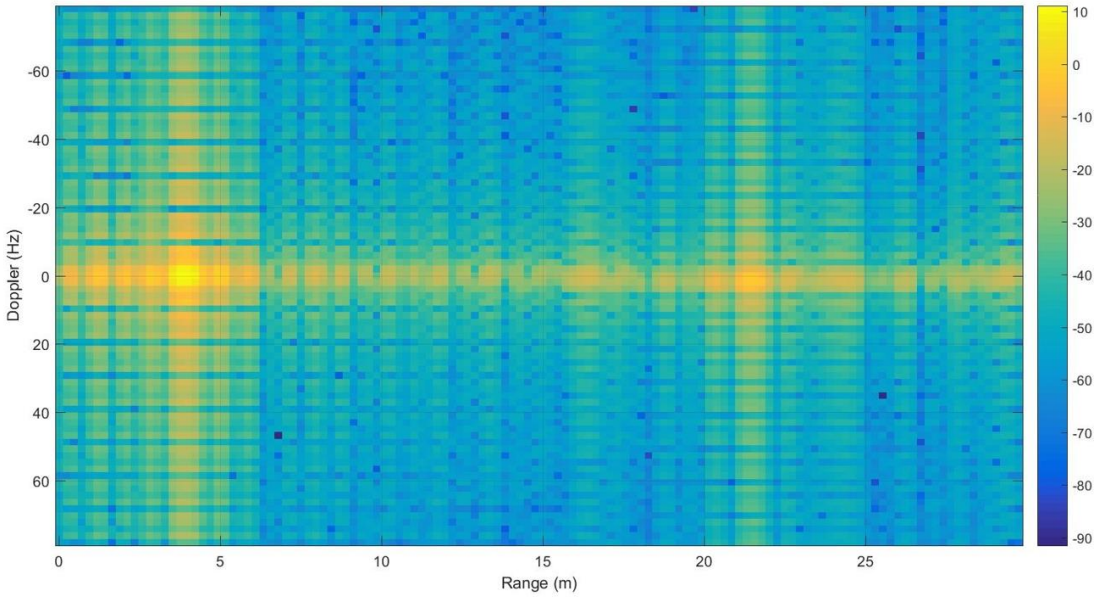

Figure 50. Background Range-Doppler Plot

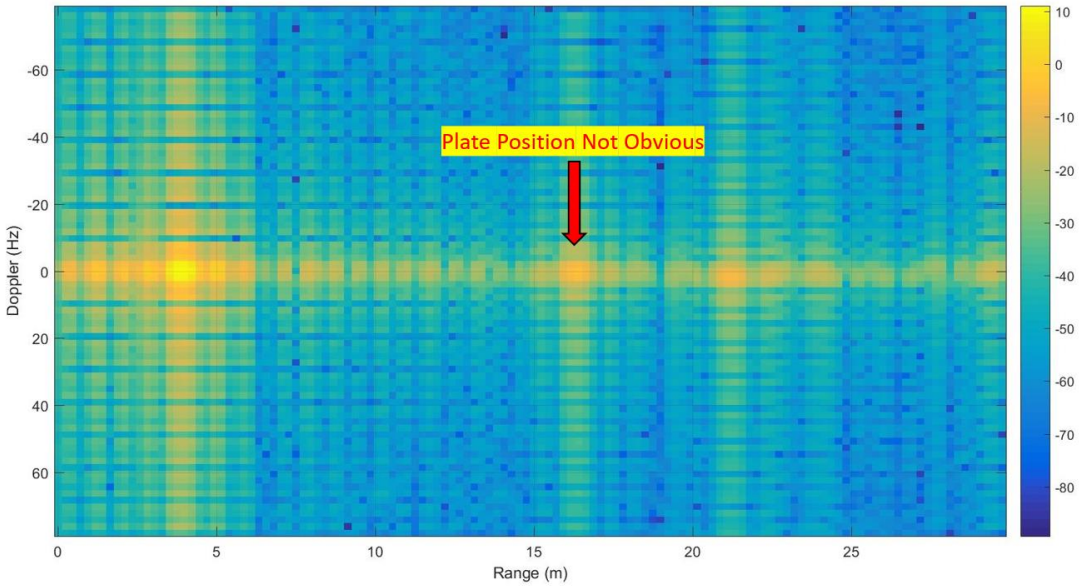

Figure 51. Plate data before subtracting Background data

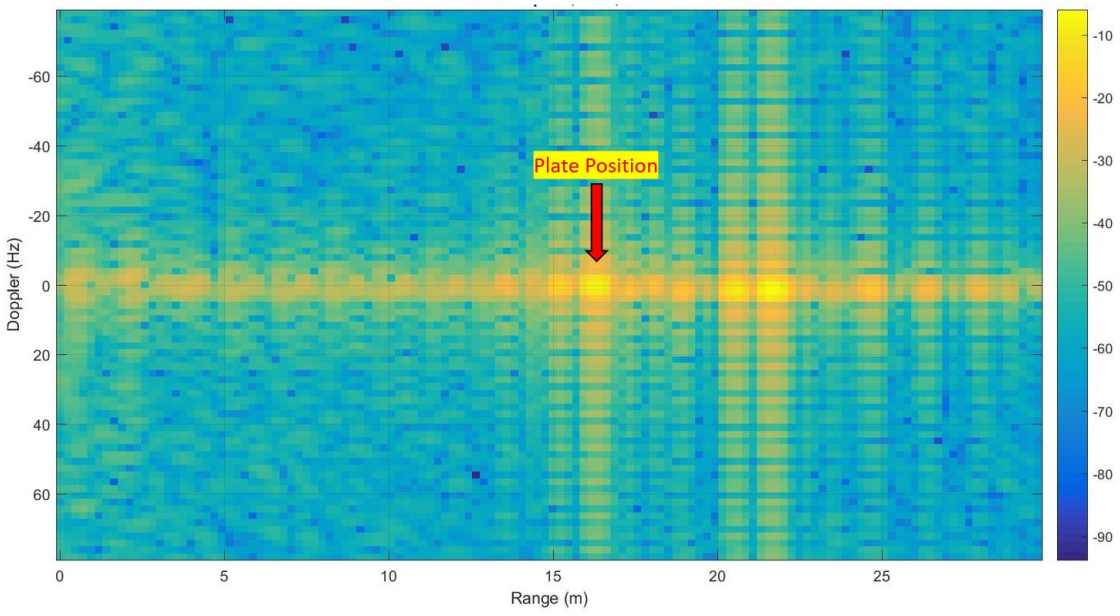

Figure 52. Plate data after subtracting Background data

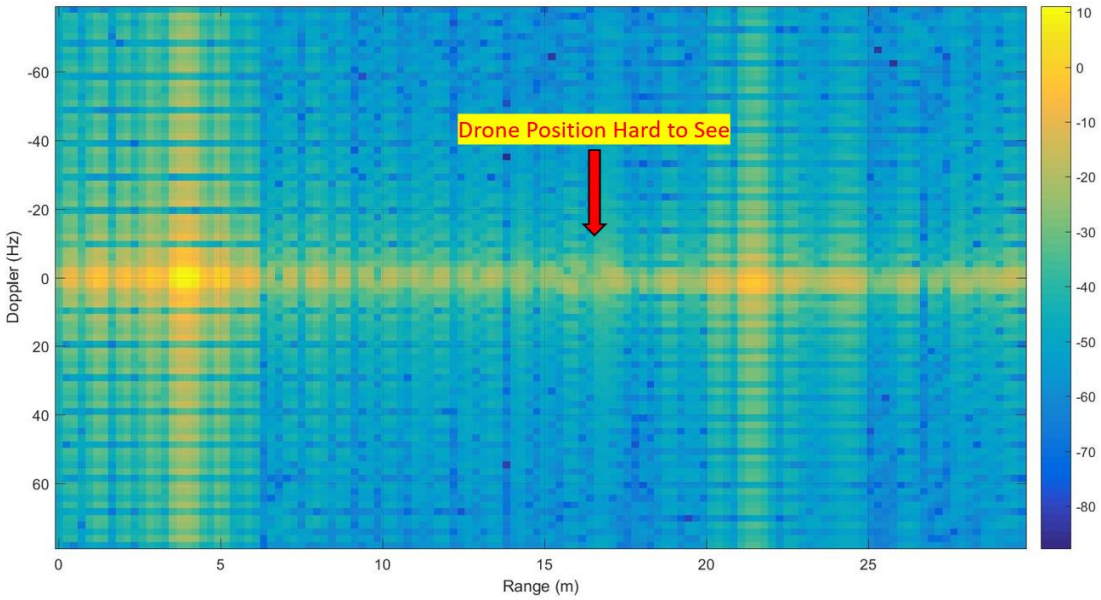

Figure 53. Drone not running data before subtracting Background data

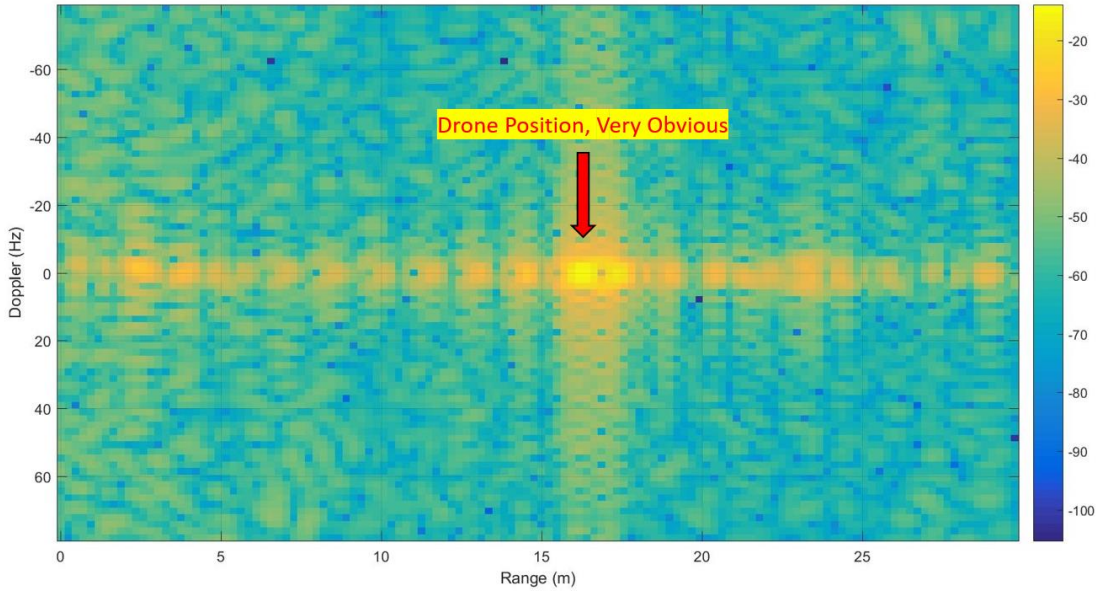

Figure 54. Drone not running after subtracting Background data

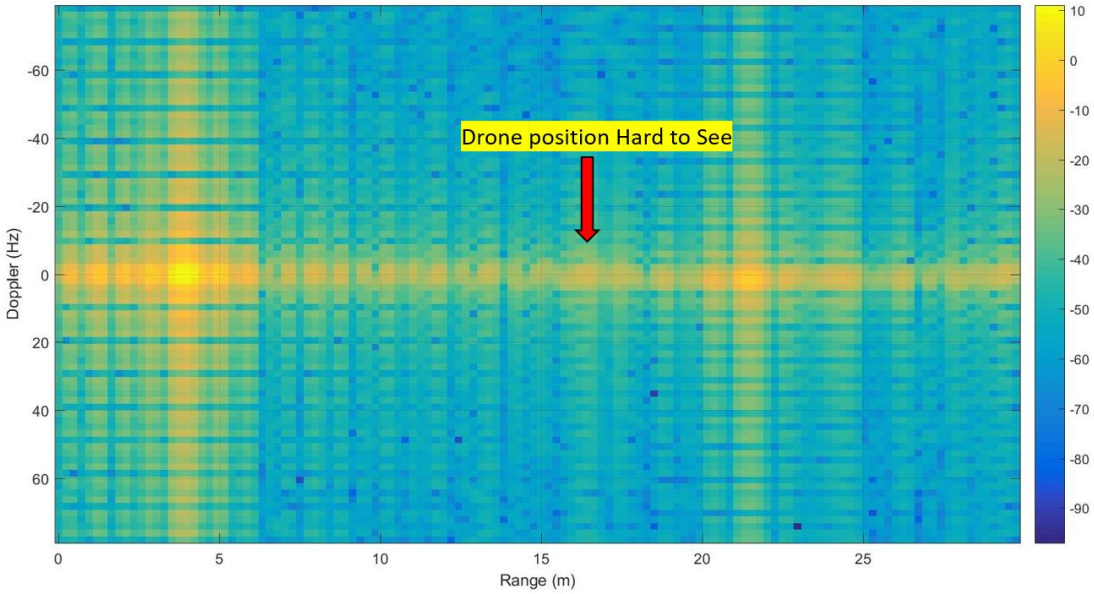

Figure 55. Drone running data before subtracting Background data

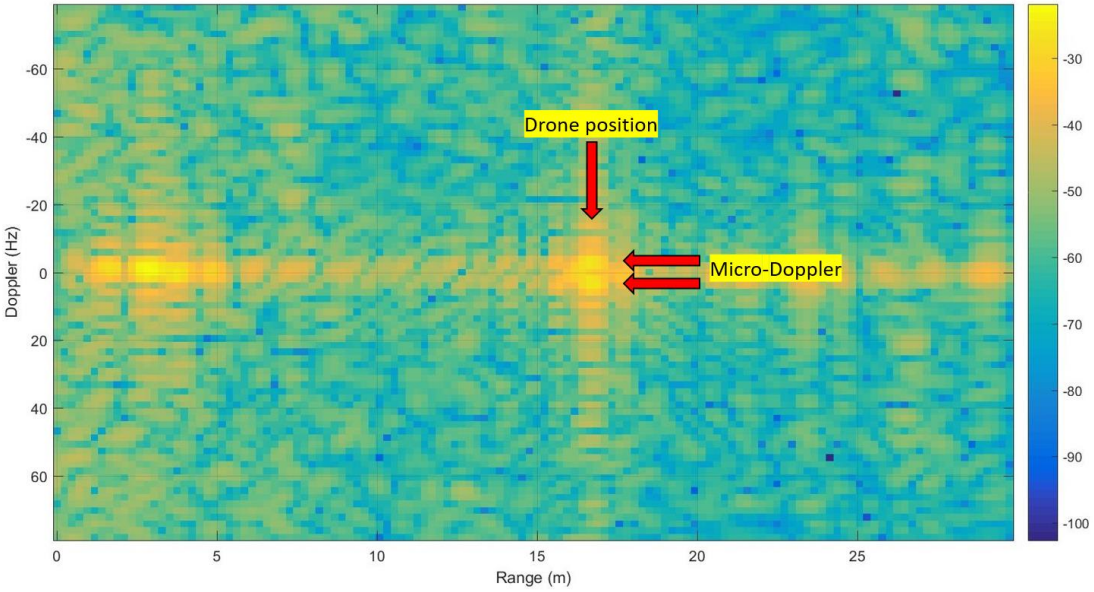

Figure 56. Range-Doppler signature of a small Drone with blade running, after subtracting Background data

Based on Figure 50 - Figure 56, we can conclude that FMCW sensor at 2.4 GHz band gives good radar target signatures for detection and characterization.

4.3 N210 and WBX Programming and Experiment Results

An FMCW Radar function program was implemented using the GNU Radio Companion. Because of N210's hardware delay, software efficiency, Ethernet speed and other reasons, an extra self-loopback test is necessary for system calibration.

In Chapter 2.4, a program was used to simulate a 3-target scenario, and the result is shown in Figure 25. The calibration program uses N210 to generate three-target signals while the TX port is connected to the RX port. The resulting range profile of the loopback calibration, as in Figure 57, is similar to Figure 25, except that the 3 targets are shifted by a specific value in range (bias value).

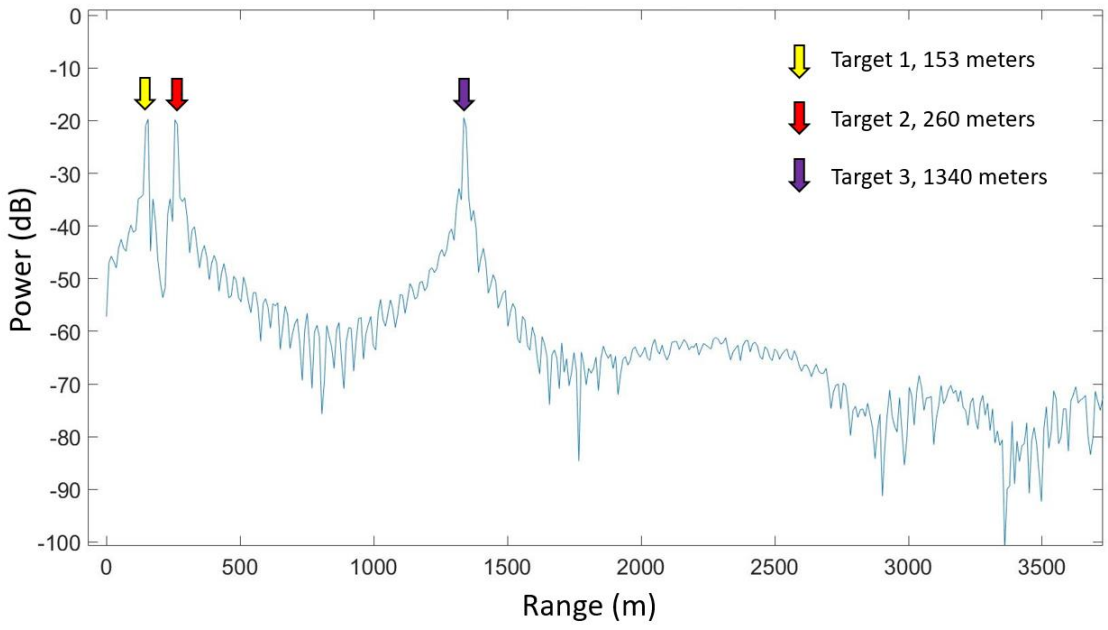

Figure 57. Simulated range profile with three targets in loopback test

Figure 25 indicates the 3 targets are in 12-meter, 120-meter and 1200-meter positions. Figure 57 shows the 3 targets are in 153-meter, 260-meter and 1340-meter positions, which means the first target shifts 141 meters, the second target shifts 140 meters and the third target shifts 140 meters comparing to Figure 25. All the shift values are around 140 meters, so “140 meters” can be considered the calibration value of N210 kit.

Figure 58 shows the system architecture of the N210-based FMCW radar implementation (which is similar to the QM-RDKIT). Figure 59 shows the configuration of the outdoor test.

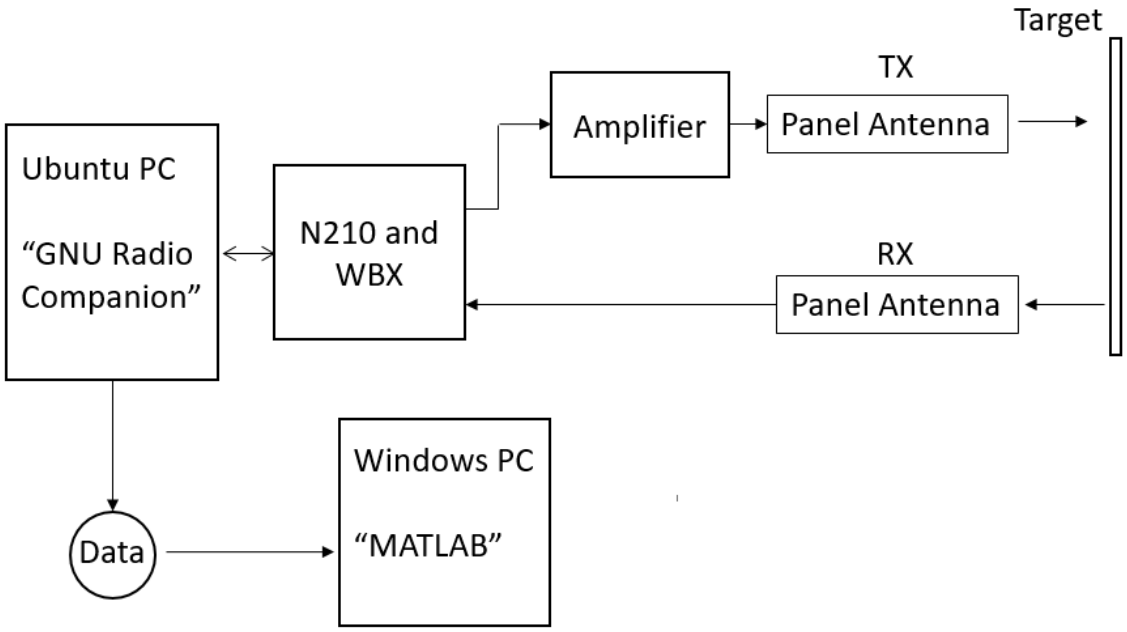

Figure 58. USRP-N210 based SDR system structure

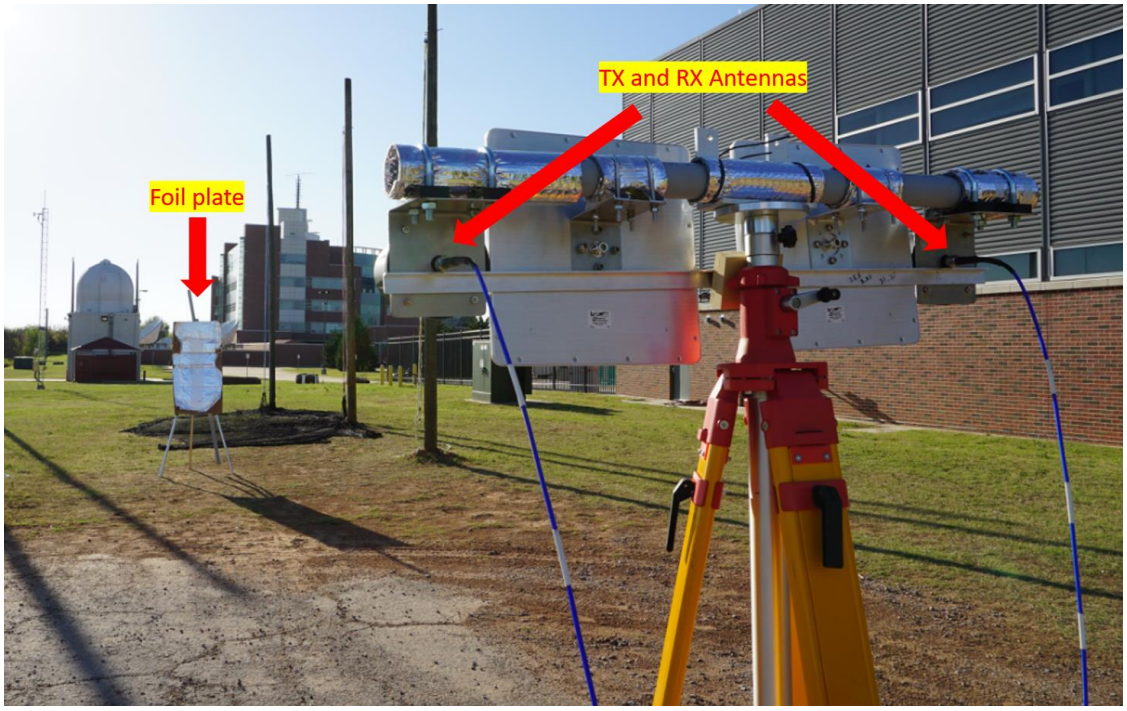

Figure 59. Outdoor experiment using N210-based SDR and a reflective plate as targets

Because the background clutter is also strong in this test, the "subtraction" method is also used in the data processing. Figure 61 and Figure 62 verify that "subtraction" is an effective approach to remove the ground clutter: the targets are difficult to see before the "subtraction", and they become easy to see after the "subtraction".

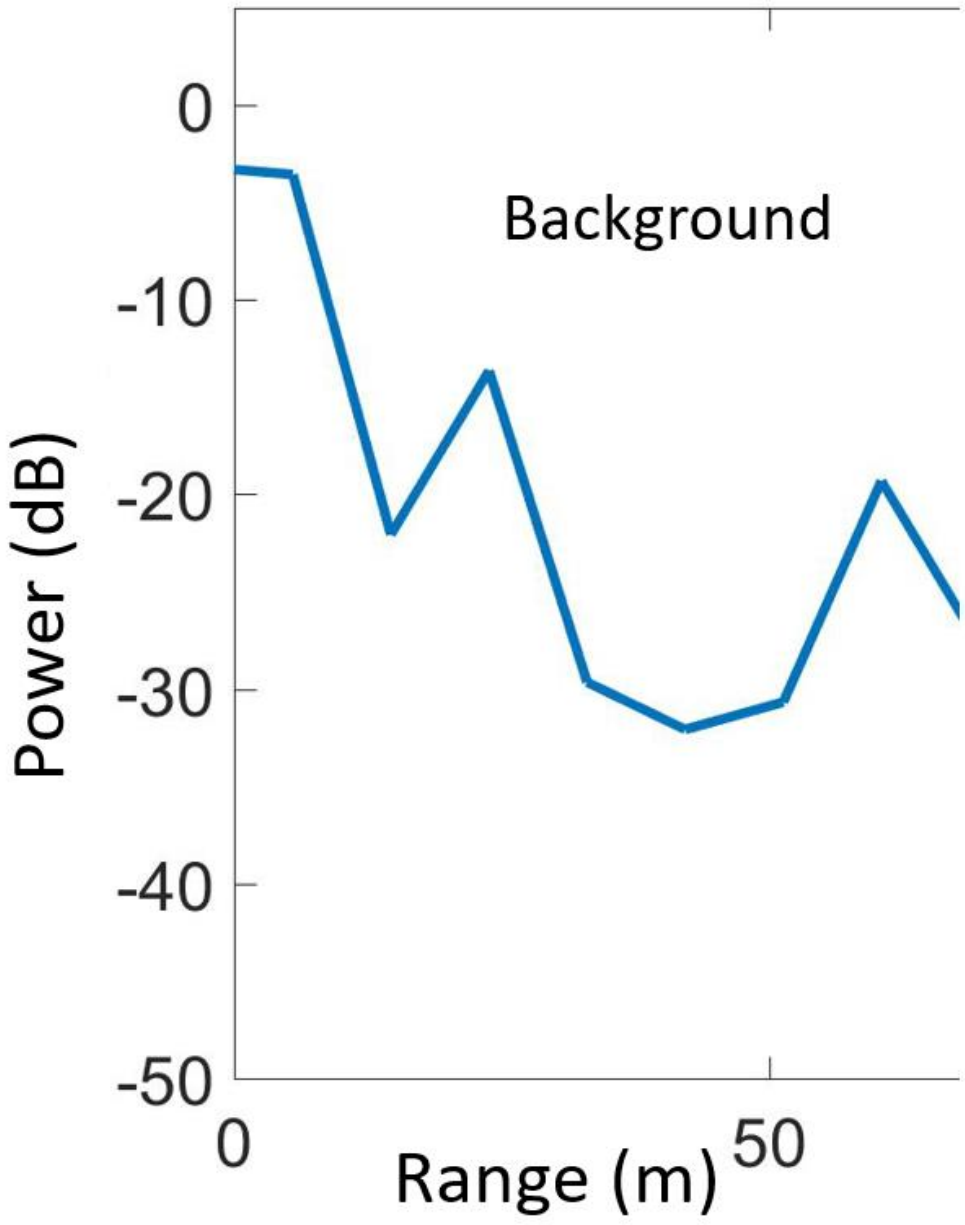

Figure 60. 1D range profile of "background" obtained from the N210-based outdoor test

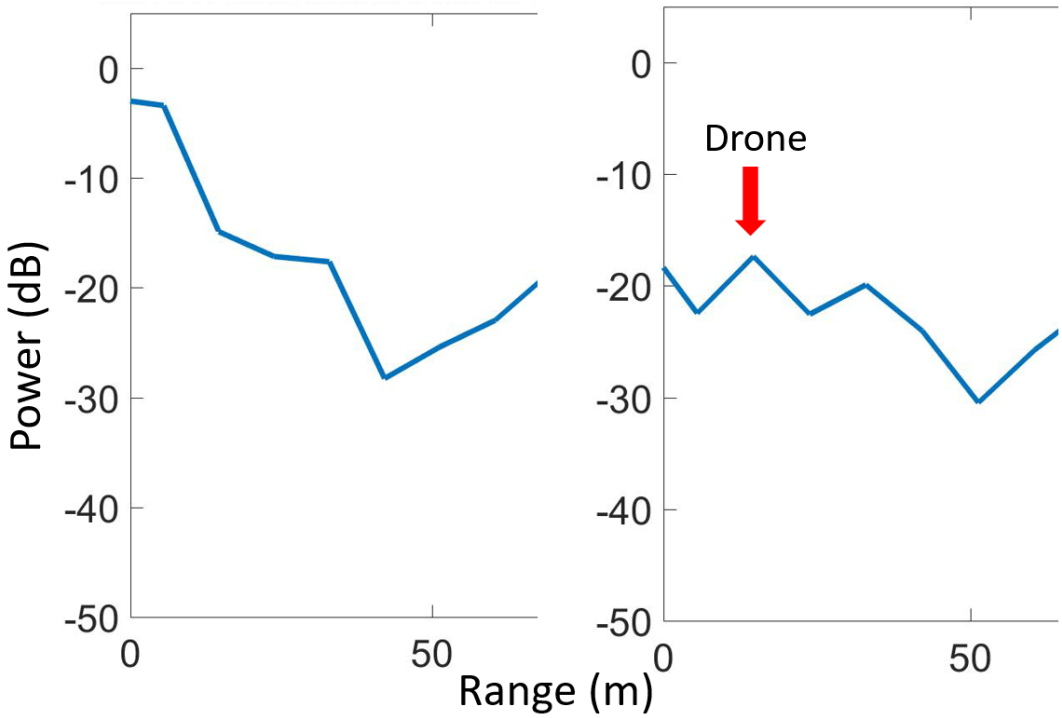

Figure 61. 1-D range plot of a single drone target

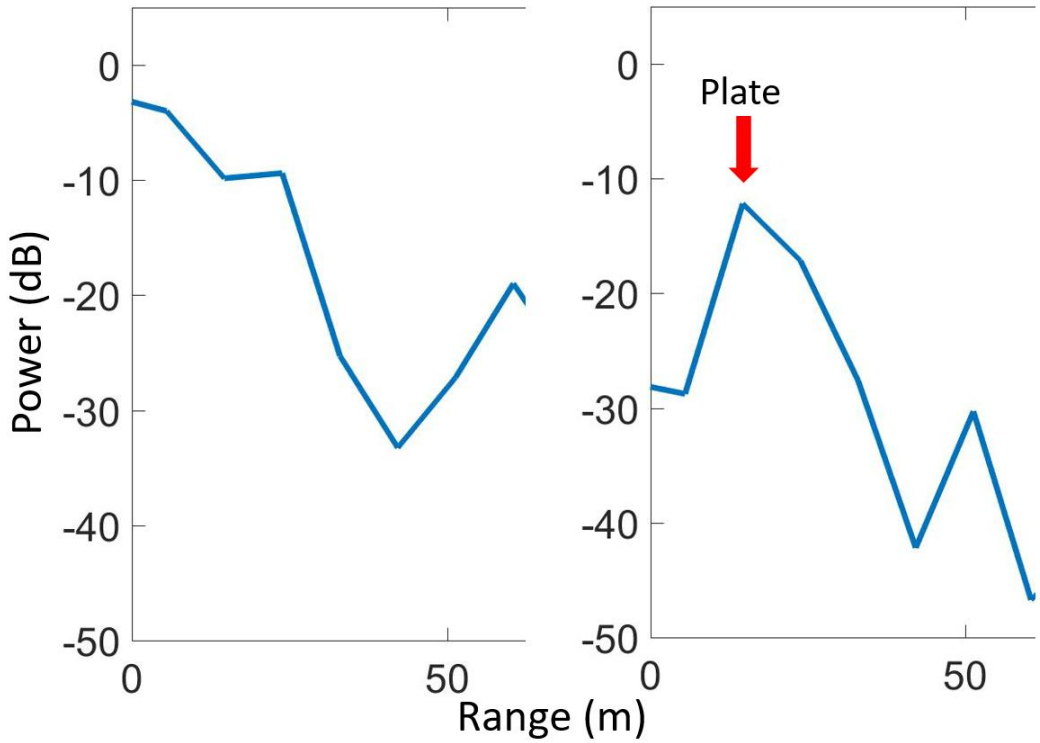

Figure 62. 1-D range plot of a reflective plate

Because the range resolution of the N210 is 12 meters, it is more interesting to observe a farther target instead of near targets. Therefore, another experiment was performed to observe a large water tower object. The configuration is shown in Figure 63.

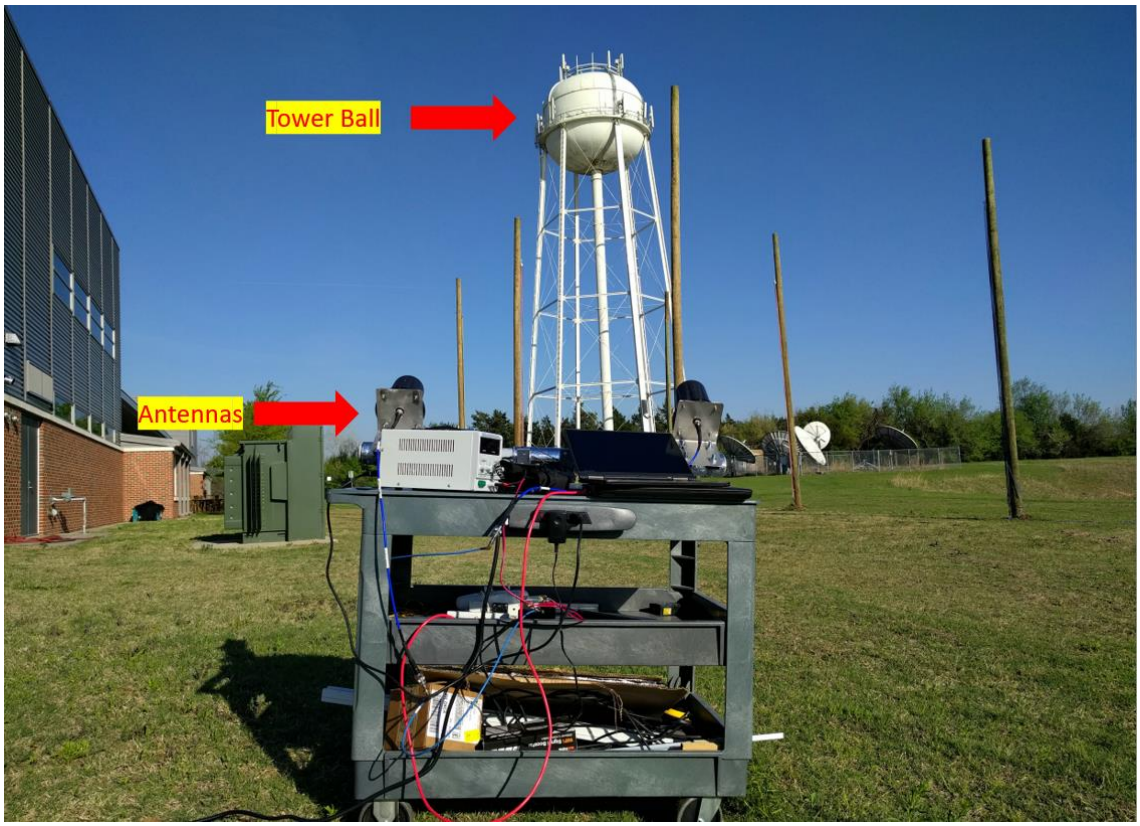

Figure 63. Water tower observation using N210-based SDR

Figure 64 shows the range profile result for this test, in which the antenna is pointed to a specific elevation angle. Further, we change the elevation angles of the antenna pointing directions and studied the impact of elevation angles on the target range signature. From 22 sets of the experiments, 6 sets of the data are selected for display, which are 16.5 degrees, 26.3 degrees, 36 degrees, 46.4 degrees, 55.6 degrees and 62.6 degrees.

In Figure 65, multiple sets of the range profile data are plotted together. Variations of the range profile can be observed. In Figure 66, each test case is plotted individually.

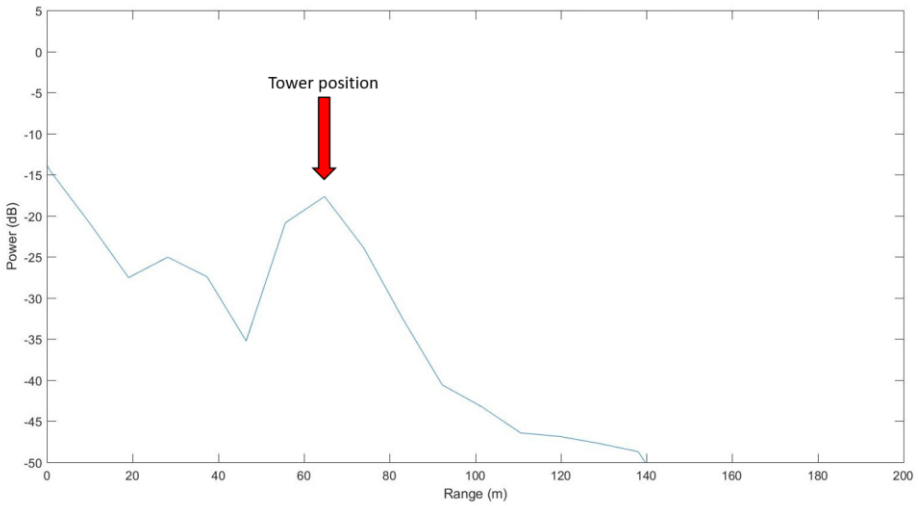

Figure 64. Water tower range profiles for a specific elevation angle of N210-based radar observation

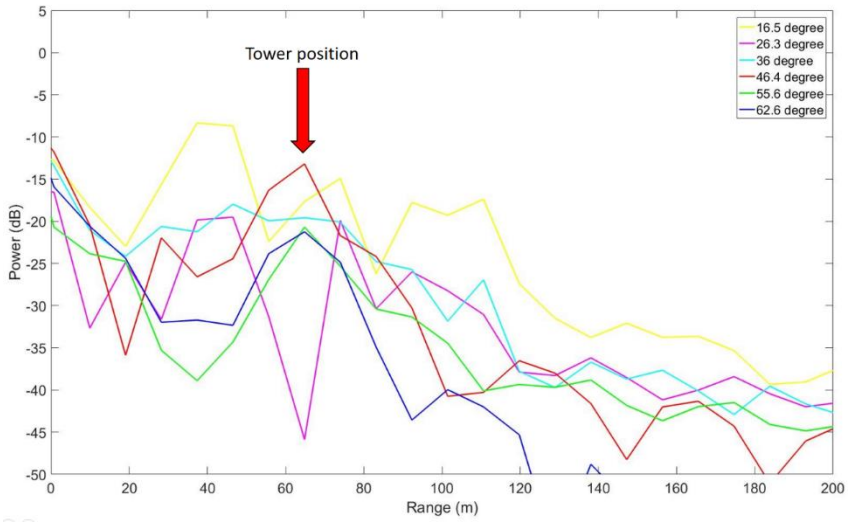

Figure 65. Water tower range profiles for various elevation angles of N210-based radar observation

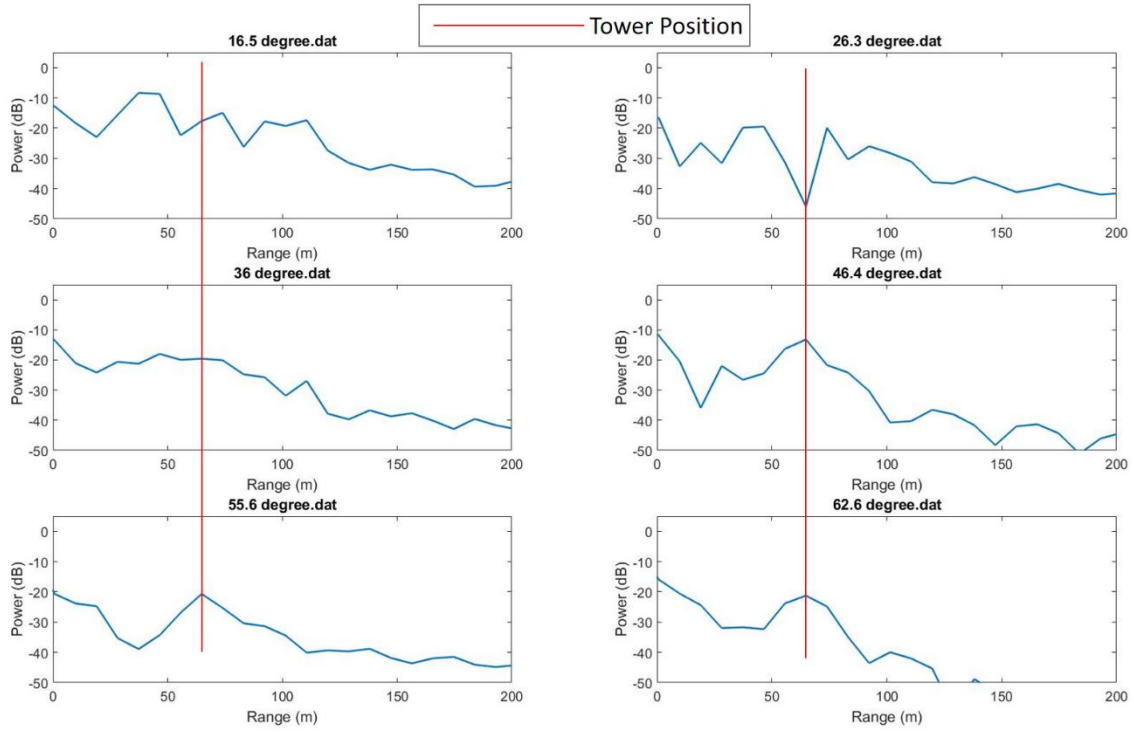

Figure 66. Water tower range profiles for six elevation angles of N210-based radar observation

The conclusion from Figure 64 to Figure 66 is that the target is not significant when the elevation angle is small. It is reasonable because a lower elevation angle means a small portion of the target is illuminated in the beam and more interference from ground clutter is reflected.

Chapter 5: Conclusions and Future Work

5.1 Summary of Work Done

The achievements of this thesis are summarized as follows:

(1) Investigated the basic principles of the FMCW radar sensors and system architectures.

(2) An SDR-based implementation of the FMCW radar sensor is achieved in both hardware (USRP N210) and software (using open-source SDR development kit). Both lab and outdoor experiments are performed and data processing results are analyzed.

(3) Compared multiple SDR platforms (including QM-RDKIT and N210 kit) for SDR implementation and performed experiments using a small drone as a target.

5.2 Future Improvements

For hardware, we can improve the results by using different types of antennas. This thesis uses two kinds of antennas, one is a horn antenna, the other is a panel antenna, which are different in size and design. A better antenna design may be able to enhance the overall SDR system sensitivity for the desired application (e.g., small drones).

GNU Radio Companion is a user-friendly software, and it uses function blocks to achieve the program goal. “Block” program is a high-level program language, so the efficiency may not be as good as classic line-coding. Increasing program efficiency can be achieved by using more low-level programming languages such as C and C++.

In addition, it is necessary to introduce improved algorithms and image processing algorithms to improve target detection performance. In outdoor tests, there is significant ground clutter. The current work used a simple coherent background subtraction

algorithm, while future work may use more sophisticated, Doppler-based clutter mitigation algorithms. Micro-Doppler information introduced by small drone targets can also be exploited as a feature for detecting and classifying such targets.

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