

Calibration and Signal Processing of Airborne Stand Profile Radar used in forest inventory

Feng Ziyi

School of Electrical Engineering

Thesis submitted for examination for the degree of Master of
Science in Technology.

Espoo 11.04.2016

Thesis supervisor:

Prof. Visa Koivunen

Thesis advisor:

D.Sc. Yuwei Chen

Author: Feng Ziyi		
Title: Calibration and Signal Processing of Airborne Stand Profile Radar used in forest inventory		
Date: 11.04.2016	Language: English	Number of pages: 7+57
Department of Communications and Networking		
Professorship: Signal Processing		
Supervisor: Prof. Visa Koivunen		
Advisor: D.Sc. Yuwei Chen		
<p>TomoRadar is a helicopter/UAV (Unmanned Aerial Vehicle) based FM-CW microwave ranging radar designed for the forest inventory. Developed by FGI (Finnish Geospatial Research Institute), TomoRadar can scan forest with Ku-band signals and then receive the backscatter signal from targets. The target distance can be figured out from the backscattered signal. Furthermore, various information around forest can be evaluated. As a ranging scatterometer the system calibration and signal processing are necessary and critical tasks. In This thesis work, these two major problems are researched and solved.</p> <p>The system calibration is limited to complete on ground and restricted in a particular range despite TomoRadar works on helicopter. Thus the range calibration experiment is conducted on the ground test field with a Luneburg lens. Besides, power calibration of system backscatter signal is researched through electrical component tests. The linearity of the radar system frequency sweep is critical in FM-CW radars. Hence, it is studied in this thesis.</p> <p>When TomoRadar works, the output of the whole system is analog signal in intimate frequency (IF) band. A digitizer samples and records the output analog signal. With these signal, the information around forest cannot be obtained. To draw stand profile of forest and research forest information, the IF band signals need to be further processed. This is signal processing part of the thesis work.</p> <p>As a result of this thesis work, TomoRadar range calibration was achieved. The calibration results were verified by the helicopter based flying tests. The results present that the calibration completed on ground test field applied with the situation that TomoRadar works in air and scans targets in long distance. The linearity of system frequency sweep generated by DDS (Direct Digital Synthesizer) is verified. Finally, the test forest backscattered data was processed and the ranges were evaluated. Some targets stand profiles are generated and presented in this thesis.</p>		
Keywords: Frequency modulation linearity; Ranging radar; Range calibration; Signal processing		

Preface

I would like express my deepest appreciation to my thesis advisor in Finnish Geospatial Research Institute (FGI) Dr. Yuwei Chen. He instructed my thesis work from constructing the whole system view to the exactly thesis work research method, moreover, he demonstrated me the strong interesting in science research, various creative ideas and persistently pursuing for distinct possibilities which are all critical for my future researching career. Without Dr. Chen's guidance and continuously help this thesis cannot be completed successfully.

I would like to thank my thesis supervisor, Professor Visa Koivunen in Aalto University. He gave me lots of professional and helpful suggestions on the system calibration methods, systematic noise study and the signal processing. With Pro.Koivunen help, I know more about radar signal processing and requirements..

Last but not least, I would like to thank my parents, they support me the whole study till the end of master. They inspire me and give me confidence to overcome frustrations all the time. Many thanks to all of my friends as well, they have been accompany with me and encouraged me, which helped me perform better without negative feelings. Thank you all of you be accompany with me for the whole winter and gave me strength.

Otaniemi, 11.04.2016

Feng Ziyi

Contents

Abstract	ii
Preface	iii
Contents	iv
Symbols and abbreviations	vi
1 Introduction	1
2 Description of Stand Profile Ranging Radar System	3
2.1 Microwave Ranging Radar	3
2.2 Radio Waves	3
2.3 System design requirements	4
2.4 System Overview	4
3 TomoRadar System Description	6
3.1 TomoRadar system overview	6
3.2 Operating frequency	8
3.3 Principle of Frequency-modulated continuous-wave radar	9
3.4 Microwave unit	11
3.4.1 DDS	12
3.4.2 Local oscillator	13
3.4.3 DC coupling	14
3.4.4 Polarization Switch	14
3.4.5 Low Noise Amplifier	15
3.4.6 Frequency Mixer	15
3.4.7 Intermediate frequency amplifier	16
3.4.8 Antenna	16
3.5 Data acquisition	17
3.6 Georeference	18
3.7 System frame	19
4 System Range Resolution Study	21
4.1 Single target range resolution research experiment	21
4.1.1 Experiment process	21
4.1.2 Results and analysis	22
4.2 Two Targets range resolution research experiment	23
4.2.1 Experiment process	23
4.2.2 Results and analysis	24
5 System Calibration and Uncertainty	26
5.1 Range calibration	26
5.1.1 Range calibration method	26
5.1.2 Range calibration result	27

5.2	Power calibration	30
5.3	Other factors effects	32
6	System Measurements and signal processing	35
6.1	System performance measurement	35
6.2	TomoRadar signal processing	36
6.3	System measurement result analysis	39
6.3.1	System SNR Research	40
6.3.2	System calibration verification	44
6.3.3	Stand profile output analysis	45
7	Conclusions	49
	References	51
A	Four channels TomoRadar signal processing with Matlab	53
B	One receiver channel data process function	54
C	Single wave form in frequency in frequency domain	57

Symbols and abbreviations

Symbols

B	Bandwidth
c	Speed of light
D	Antenna diameter
G_{if}	Intermediate frequency amplifier gain
H	Horizontal
λ	Wave length
m	Mass of antenna
r	Antenna radius
h	Antenna thickness
ρ	Antenna material intensity
f_{if}	Intermediate frequency
f	Frequency
f_b	Ground echo beat frequency
f_{bl}	Leakage signal beat frequency
δf	Frequency resolution
δR	Range resolution
R	Target range
R_g	Range to ground
R_2	Coefficient determination
r_l	Leakage path length
SS_{tot}	total sum of squares
SS_{res}	the sum of squares of residuals
V	Vertical
\bar{y}	Data mean value
θ	Antenna beam width

Abbreviations

AGC	Automatic gain control
DC	Directional Coupler
DDS	Direct Digital Synthesizer
DEM	Digital Elevation Model
FM-CW	Frequency modulation continues waveform
FGI	Finnish Geospatial Research Institute
GNSS	Global Navigation Satellite System
IMU	Inertial Measurement Units
IF	Intermediate frequency
LNA	Low noise amplifier
LO	Local Oscillator
NI	National instrument
PDF	Probability density function
PSD	Power spectral density
RF	Radio frequency
RCS	Radio Cross Section
SAR	Synthetic Aperture Radar
SNR	Signal noise ratio
TTL	Transistor–Transistor Logic
UAV	Unmanned Aerial Vehicle
VSWR	Voltage Standing Wave Ratio

1 Introduction

Microwave radar is attractive in vegetation inventory for its high penetration capability. The idea of measuring tree height and density in forest using airborne radar is described first by Bernard et al.[1]. Afterwards, more researches on vegetation inventory using Synthetic Aperture Radar (SAR) data have been conducted in past decades. Some researches focus on crops, e.g. soil condition, leaf area of crop canopy [2] [3], relationship between backscatter signal over rice and the biological variables [4]; While others focus on forest inventory, including the estimation of tree height, volume and surrounding biomass [5][6]. However, the limitations that survey area specifically, backscatter signal saturation and high cost of airborne radar system block the inventory of forest with microwave radar data. Thus to promote the microwave data application in forest or other areas inventory, it's significant to research airborne microwave radar system.

A helicopter-borne ranging radar system named HUTSCAT was designed and demonstrated by Hallikinan, Hyyppä et al. in [7]. This ranging radar works in C- and X-band with maximum eight polarization modes, and the range resolution is 0.65 meter. To research forest with HUTSCAT the backscattered signals of targets are collected and converted into frequency domain in the system. Then the tree height and other related variables are estimated based on the corresponding backscatter signal frequency [8]. [9] [10] discussed the applicability of HUTSCAT to forestry inventory. With HUTSCAT, it's possible to assess forest by scanning the forest directly.

However, limited by the technologies, there are problems with HUTSCAT. The range resolution of HUTSCAT is only 0.65 meter which means it can only determine the distributed targets. As in HUTSCAT, the collected data is real time processed and stored in the disc driver, the measurement area is limited because of limited working space. In addition, the whole system is heavy with a large size support structure which is not convenient for flying measurement.[11]

A helicopter/UAV (Unmanned Aerial Vehicle) based waveform radar called TomoRadar is being constructed in FGI (Finnish Geospatial Research Institute). Similar with HUTSCAT, TomoRadar is a ranging radar which collects the backscatter signal of trees and then evaluates the range and height of tree. TomoRadar has the capability of investigating large forest area one time as it performs real-time FFT transform of the collected backscatter signal waveforms in software. TomoRadar employs Ku band and works in four polarization modes offering distinct information. System calibration and radar signal processing of TomoRadar are done in this thesis work. Furthermore introduction of TomoRadar will be given in chapter 3.

To acquire more accurate range evaluation from the returned signal spectral, it is essential to calibrate the radar system carefully every time before the fly test. Consider the difficulty of obtaining real distance from radar to target when TomoRadar working in a flying helicopter, as well as the flying experiment cost, calibrating the system in the air is not realistic. The easiest way is to complete the calibration on ground. For TomoRadar system, the ground calibration experiment is carried outside of FGI laboratory room where the space is limited. The maximum calibrated range in the

ground test field is 40 meters, compared with TomoRadar system probe distance 10 to 150 meters it is not long enough to guarantee calibration result covering the whole measurement range. In addition, the experiment environment is complex in most laboratories. In FGI ground test field, there are trees and grass around which produces backscatter signals to affect target echo. To mitigate the total echoes reflected by the surroundings, the calibration range for radar probe distance has to be restricted to assure the major part of footprint reflected by the Luneburg lens. Hence, the calibration should be carried in restrict range even the experiment space is sufficient. Considering the significance of system calibration and the above limitations, the calibration process has to be designed and completed carefully.

On the purpose of pursuing better system range resolution, TomoRadar employs 1 GHz bandwidth to achieve 15 cm system range resolution. Nevertheless, the increasing of bandwidth leads to the decreasing of frequency sweep linearity, which results in range resolution degrades [12]. Hence, it's critical to maintain and detect the modulating linearity in FM-CW ranging radar. Several methods were proposed to produce linear frequency band, in which DDS (Direct Digital Synthesizer), adopted in TomoRadar, is highly recommended for its superior linearity performance in waveform generating [13]. However, even the linearity property of DDS has been researched and proved, it is still necessary to make sure about that in TomoRadar due to the individual system difference.

As said before, in TomoRadar the collected backscatter signal is processed in software which improves TomoRadar scanning ability. The complexity of radar data processing is another factor which adds forest inventory workload. Hence, it is important and useful to pre-process the radar data before doing other analysis.

Via this thesis work, I learnt to construct system view when starting to study system issues. I recognize how it is important to have an overall cognition of the system before analyzing it. In addition, I practiced to design an accurate scientific experiment for a practical system and completed it. My ability of microwave data processing by Matlab is enhanced as well. Overall, in this thesis work, a microwave radar system ground calibration method was proposed and completed, and the calibration effects were verified by the radar practical experiments results. The radar system power calibration was proposed and studied. And then, the system frequency sweep linearity is verified as well based on the system calibration results. Finally, the microwave radar experiments data preliminary processing was done with Matlab and some stand profile diagrams were generated to briefly demonstrate the profiling radar functionalities. However, the system power calibration is not completed well and still under studying. In the data processing part, the combination of radar data and georeference data is not accomplished in this work.

Besides introduction there are six more chapters. Chapter 2 explains ranging radar basic theories and the new system design requirements; chapter 3 explains TomoRadar system structure and features; and chapter 4 presents the system range resolution study; while in chapter 5, both the range and power calibration are discussed; chapter 6 presents the system performance through measurement results and finally some conclusions are given in chapter 7.

2 Description of Stand Profile Ranging Radar System

2.1 Microwave Ranging Radar

Radar is an object-detection and -location electromagnetic sensor. The electromagnetic energy is propagated to expected directions from the antenna of radar transmitter. Some energy that is accepted by object, usually called target, is reradiated to various directions. The collected backscattered energy by receiver antenna is named echo and processed afterwards for further analysis [14]. Radar targets can be ships, forests, and icebergs, etc., in addition, the radar carrier might be buildings, airplanes, or satellites, etc. for distinct purposes. Nowadays, various radar applications have been developed for different utilities.

Comparing with laser light, microwave has relatively stronger penetration ability which enables the propagated energy to bypass objects, e.g. trees, buildings. Consequently, microwave is suitable for forest inventory. Information including range, direction, angular size and shape of detected targets could be obtained from radar. TomoRadar is designed to be a ranging radar which collects target echoes and presents the target range, size and shape.

2.2 Radio Waves

Radio waves are parts of electromagnetic radiation with the frequencies in the range of 3 KHz to 300 GHz, the corresponding wavelengths vary from 100 kilometers to 1 millimeter. The waves travel in the free space at the speed of light (c) which is the product of wave length (λ) and the corresponding wave frequency (f).

$$c = \lambda * f, \quad (1)$$

Where c is exactly 299 792 458 m/s (approximately $3.0 * 10^8$ m/s). Obviously the wave length is inversely proportional to the wave frequency. Each radio wave with certain wave length has specific performance when propagating in the air. For the waves, the longer the wavelength is the easier the wave penetrates obstacles. However, the transmitter and receiver antenna design limits the selection of operating frequency band. In addition, same targets might have different reactions for waves with distinct frequencies. Therefore, various radio frequency bands are researched to find the specific information on same target.

The system transmitting and receiving polarization refers to the polarization of operating electromagnetic waves. It is defined as the electric field orientation. An electromagnetic wave can be divided into two orthogonal vectors. The phase difference between the two components leads to the sum of the vectors over time is an ellipse. If the difference was 0 which means the two waves work in same phase, the resulting ellipse would be a straight line and the polarization is linear. Another specific situation is the difference is 90 degrees, in which case, the ellipse will become to be a circle. The specific vertical (V) and horizontal (H) polarizations belong to the linear situation. Based on these two polarizations radar system can work in

different modes. When the energy polarizations are same in transmitter and receiver which can be short presented by HH and VV, it is so called co-polarization mode. Otherwise, they are cross-polarizations with the abbreviation of HV/VH.

2.3 System design requirements

The system is required to be a helicopter/UAV-borne profile radar system. Low altitude measurement over forest can be done with this system to collect data efficiently. The application constructed with the helicopter-borne radar system is forest remote sensing. The designed application function including assessment of certain forest area, backscatter signal distribution of the forest canopy and evaluation of forest pass through attenuation.

When system works over forest the flight height is required to be in the range of 50 to 100 meter. However, in order to master a good margin the designed minimum fly height should be around 10 meters. The antenna beam width is approximately 6 degrees. As the radar platform is helicopter/UAV the system weight should be as light as possible to guarantee properly performance of the system, especially for UAV-borne version. In addition, the system power consumption should be low enough to support the system long period working tasks and eliminate the risk of components damage.

As said before the object reactions for different electromagnetic energy components are distinct. On the purpose of comparing measurements data and evaluating forest exhaustive, four polarization modes are required on the ranging radar system. What's more, the multiple polarization modes should operate simultaneously for the accuracy of comparison results.

Isolation between antenna polarizations should be high to offer reliable results for the cross-polarization mode. Generally, the isolation is at least 30-dB. The isolation in the system radio unit is critical as well. Hence, isolators should be employed to prevent ripple in the circuit.

High measurement accuracy of backscattering coefficient with good range resolution are required for the measurement of small target with weak backscatter signal. Therefore, the noise floor of system should be kept at a low level.

System calibration should be carried every time before the ranging radar system working. It eliminates the variations in the backscattering coefficients caused by different target range.

2.4 System Overview

The stand profile ranging radar system is developed for forest inventory. With independent transmitter and receiver antennas, it works in four polarization modes (HH, HV, VV, and VH) simultaneously. The backscatter signal of targets are collected by radar receiver and processed instantly by a digitizer. From the display of digitizer, the real time probe results can be checked. Making use of the backscatter signal frequency, the targets range are evaluated. Furthermore, the information around

trees including tree height, shape are estimated. The original recorded data has been recorded for the afterwards researching work.

Besides the radar system, some addition equipment is adopt when working over the forest. The georeference system consists of a high quality GNSS (Global Navigation Satellite System) receiver and a tactical grade IMU (Inertial Measurement Units). They are used during the radar system flying test to help record the helicopter fly trajectory and synchronize position and time. Figure 1 presents the block diagram of designed ranging radar working environment.

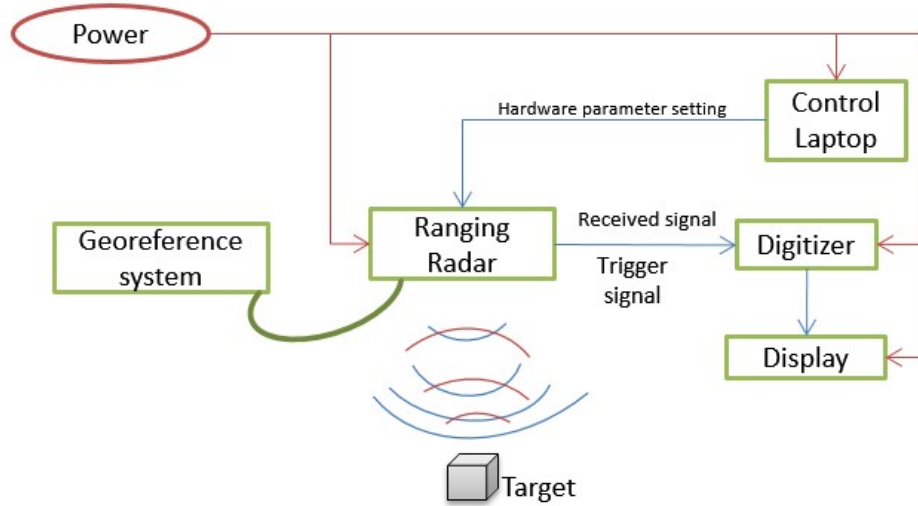


Figure 1: Ranging radar system working situation overview

As TomoRadar is designed to be helicopter/UAV-borne, it has to be as light as possible. The weight of the whole TomoRadar system on helicopter is less than 13 Kg including the georeference instruments, while it is designed to be less than 7.2 Kg for UAV version including 20% weight margin. The mass of major sub-system of TomoRadar is listed in Table 1.

Table 1: The mass of the sub-systems of TomoRadar

Sub-system	Quantity	Mass(gram)
Antenna with OMT	2	1800
RF+IF Unit	1	1800
Georeferencing System	1	4600(Helicopter)/600(UAV)
Digitizer	1	<5000(Helicopter)/1000(UAV)

3 TomoRadar System Description

As introduced before, the stand profile ranging radar has been developed by FGI and named TomoRadar. Until now, both helicopter and UAV-borne versions of TomoRadar system implementation have been done. Helicopter based flying tests of TomoRadar have been carried for three times in different months (July, October and December, 2015), and the seasonal particular information from same forest was obtained. At this moment, Efforts are devoted in the improvement of backscatter Signal Noise Ratio (SNR) and power source module. A detailed description of TomoRadar is given in this chapter. Figure 2 presents the TomoRadar system with the frame when system calibration was carried on ground.



Figure 2: TomoRadar works for calibration

3.1 TomoRadar system overview

Working in Ku band, TomoRadar works based on the principle of Frequency Modulated Continuous Waveform (FM-CW) with linear frequency sweep waveforms. The target range can be acquired from corresponding backscatter signal intermediate frequency. For better isolation performance two antennas work in TomoRadar as transmitter and receiver respectively. What's more, the two antennas support four polarization modes of HH, VH, HV, and VV. In this system, real time FFT transform of the backscattered signal is performed in software to simplify the system hardware design. The technique information of TomoRadar is presented in Table 2.

It can be seen that the antenna beamwidth is about 6 degree which is larger than that in HUSCAT. This is because of the radar system size and weight limitations. To pursue lower antenna beamwidth, then larger and more expensive antenna is

required which is difficult to design when considering installed on both helicopter and UAV. Another thing is about the incident degree which is 0 degree in TomoRadar at this moment. Multiple incident degrees measurements can be realized by designing special mechanical radar system support frame. This may be done in future.

Table 2: Technical Characteristics of TomoRadar

Parameter	Specified value
Frequency	14.0 GHz
Sweep Frequency	1 GHz(13.5~ 14.5GHz)
Polarization modes	HH,VV,HV,VH (H= horizontal polarization) (V= vertical polarization) (HV= transmit in H mode and receive in V mode)
Measurement range	10~ 150m
Range resolution	0.15 m
Spatial resolution	two-way antenna beamwidth < 6°
Frequency band	Ku band
Incidence angle	0 degree nadir
Modulation type	FMCW
A/D converter	12 bits
Intermediate Frequency range	>20K
Antenna size	33 cm
Modulation Frequency	163 Hz
Position accuracy	1cm + 1 ppm
Radar Control	PC AT computer
Dynamic Range	> 50 dB
Data Rate	2.5 MS/S
IMU data rate	200 Hz
Attitude Accuracy	Roll: 0.005 degree
	Pitch: 0.005 degree
	Heading: 0.008 degree
Gyro Rate Bias	<1 degree/ hr
Accelerometer Bias	<1.0 mG

When TomoRadar running in helicopter, a National Instruments (NI) PXie- 6115 works as a digitizer which samples collected backscatter signal and demonstrates the real time data in both time and frequency domain. In addition, TomoRadar adopts a Novatel tightly coupled GNSS-IMU system as georeference solution which helps record fly trajectory. After data acquisition is done, afterwards analysis will be completed in Matlab.

3.2 Operating frequency

The typical radio frequencies for ranging radar are C-band, X-band, Ku-band and Ka-band. As TomoRadar is designed to be helicopter/UAV based radar, short size and lightweight antenna becomes to be an important factor when selecting the operating frequency. Consequently, the system operating frequency would be a result of compromise between antenna size and range resolution. Based on this consideration C-band which needs large antennas is no longer considered. When it comes to Ka-band which obviously allows smallest antenna, its extra requirement for the waveguide components counteracts the benefit of smaller antenna. Therefore, the operating frequency have to be selected between X- and Ku-band.

Assume the antenna type is parabolic dish antenna. As the required antenna beam width is approximately $\theta_{3dB}=6^\circ$, the radar foot print radius is around 5 meters when fly height is 50 meters, and 10 meters when the fly altitude is 100 meters. In addition, the frequency of X-band and Ku- band are assumed to be 10 GHz and 14 GHz respectively. With these assumption and design requirements, the antenna size and weight can be calculated for these two frequency bands. For a round aperture half power beam width is approximately

$$\theta_{3dB} = 1.27 * \frac{\lambda}{D}, \quad (2)$$

In which λ is the wavelength and D is the antenna diameter. Through equ. 2 the antenna dish diameter can be figured out to be $D_{x-band}=0.36$ m and $D_{Ku-band}=0.26$ m.

Besides the antenna size, the weight should be considered as well. To estimate the antenna dish weight, the dish thickness and material type are related. If assumed the antenna material is aluminium (density $\rho =2700\text{kg/m}^3$) and the thickness h is 2 mm. The relation between weight (m) and those two parameters is

$$m = \pi r^2 h \rho, \quad (3)$$

Through equ.3, the antenna dish mass can be calculated as $m_{x-band}=0.55$ kg and $m_{Ku-band}=0.29$ kg. Considering the antenna support structures, the total mass will be larger much.

As TomoRadar is designed to work in UAV and through the system design two antennas are employed. In addition, the weight requirement for the whole system is 5 kg (excluding the georeference system and data collection part). Considering all requirement and risk, Ku-band is more promising for the system.

What's more, Ku-band has been selected as operating frequencies in many space borne scatterometers, for example SASS (1978), NSCAT (1996) and Seawinds (1999) [15]. These scatterometers performed well and useful data has been collected and analyzed for much more different research purposes, such as sea ice identification [16] and the wind effects on weather forecasting [17]. Therefore, the Ku-band should perform well in the radar system. In addition, with TomoRadar successfully developed, the data collected by TomoRadar can be compared with the data collected by the above mentioned scatterometers to make clearly about the difference among the data.

If the data collected by TomoRadar was verified to be enough for the related area researches, the research data collecting would be easier compare with getting data from space-borne scatterometers.

3.3 Principle of Frequency-modulated continuous-wave radar

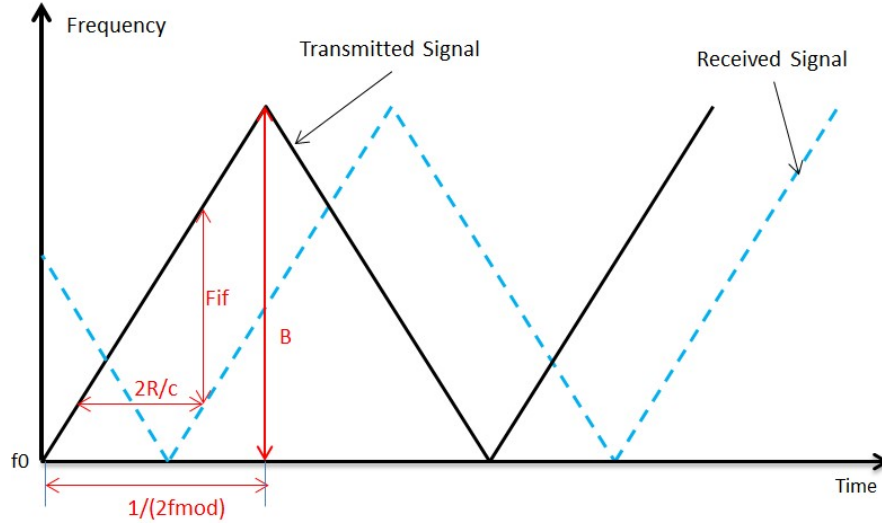


Figure 3: Principle of FM-CW radar

FM-CW radar has the advantages of relative low purchase cost and power consuming [18]. In TomoRadar, Transmitted microwave power is frequency-modulated in continuous low frequency triangular waveforms. The transmitted waveforms are compared with the backscatter signal of target. There is time delay between transmitted and received signals which causes frequency difference between these two signals at the same. With the parameters system bandwidth (B) and system modulation frequency (f_{mod}), combining with the frequency difference which is named intermediate frequency (f_{if}), the target range can be estimated. The principle of frequency modulation is presented in Figure 3. More details around the process is described in following part.

As shown in Figure 3, the frequency of transmitter signal changes as time goes. Assume the signal frequency is f , it can be presented as

$$f = K * t, \quad (4)$$

Where, K is the rate between frequency and time. Thus the modulated signal can be expressed as

$$y(t) = A_c \cos(\omega_c t + 2 * \pi * K \int_{-\infty}^t t dt), \quad (5)$$

In which A_c is the amplitude of carrier signal and ω_c is the carrier signal frequency. Finally, the equation can be obtained

$$y(t) = A_c \cos(\omega_c t + 2 * \pi * K \frac{t^2}{2}), \quad (6)$$

The backscatter signal from target after certain time delay (T_p) can be expressed as

$$y(t - T_p) = A_c \cos[\omega_c(t - T_p) + 2 * \pi * K \frac{(t - T_p)^2}{2}], \quad (7)$$

More mathematics explanation will be performed in system mixer part. Analyze the backscatter signal from Figure 3, the relation between target range and backscatter signal frequency can be figured out. Assume the time interval between transmitted signal and the received backscatter signal is T_0 and intermediate frequency f_{if} (beat frequency), then it can be obtained

$$\frac{f_{if}}{T_0} = \frac{B}{1/(2f_{mod})}, \quad (8)$$

As $T_0=2R/c$, where R is the range between target and radar transmitter, the equation can be expressed as

$$\frac{f_{if}}{2 * R/C} = \frac{B}{1/(2f_{mod})}, \quad (9)$$

Therefore the ratio between target range R and backscatter intermediate frequency f_{if} is

$$\frac{f_{if}}{R} = \frac{4Bf_{mod}}{c}, \quad (10)$$

In which, c is the light speed, B is sweep bandwidth and f_{mod} is the system modulation frequency. Equ.10 is employed when evaluating target range from TomoRadar scanned backscatter signal intermediate frequency.

In the ideal situation, the frequency change of the modulation process should be linear as shown in Figure 3 which means the frequency increasing ramp rate should be a constant value. Such linear property affects system range resolution. The radar system range resolution (δR) describes the minimum distance between two reflectors that can be recognized independently from backscatter echo signal frequency spectrum. Assume the frequency resolution is δf , it can be expressed as

$$\delta f = \frac{df_{if}}{dt} = \frac{1}{T_b/2} = 2f_{mod}, \quad (11)$$

Combing equ.(10) and equ.(11) the target range R and range resolution δR are

$$R = \frac{c}{4Bf_{mod}} f_{if}, \quad (12)$$

$$\delta R = \frac{c}{4Bf_{mod}} \delta f_{if} = \frac{c}{2B}, \quad (13)$$

With the parameter values c is approximately $3 * 10^8$ m/s and the sweep bandwidth is 1 GHz, the system theoretical range resolution is 0.15 m.

Through equ.(13) the system theoretically range resolution is only related with the system modulation sweep bandwidth. The wider the bandwidth is, the better the range resolution will be. However, there are some limitations blocking the further

improvement of range resolution. On one hand the analog waveform generator capability is limited, at this moment the maximum signal frequency produced by the DDS used in TomoRadar can be 1.5GHz, however, on the purpose of avoiding more hardware usage only 1 GHz is applied. To improve the range resolution from generator aspect, the waveform generator with higher upper frequency limitation, but at reasonable cost have to be selected. On the other hand, the previous analysis is based on the ideal case in which the sweep frequency increases linearly completely. However, in real system the linearity of sweep frequency cannot remain same as the sweep bandwidth increases, which has negative effect on the range resolution. The verification of system sweep frequency linearity is partly of this thesis work and will be researched and discussed more in following chapters.

3.4 Microwave unit

The block diagram of TomoRadar microwave unit is shown in Figure 4. Except the left corner part in Figure 4 belongs to low frequency signal, the other circuit parts work with radio frequency signal. There are major two chains in which the upper line belongs to transmitting part, while the lower parts present the receiver part.

First of all the triangle frequency sweep is generated by DDS. To propagate the signal with microwave antenna, the signal is up converted into the radio frequency band where center frequency is 14 GHz. The transmitted signal frequency range is 13.5 GHz to 14.5 GHz. After band pass filter and amplifier, the signal is divided into two parts with same frequency by DC coupling. One part is transmitted by the antenna after polarization switching; the other part goes to a splitter which divides the signal into two parts again. The two same signals are transmitted into the mixers in receiver chain. The two mixers receive horizontal polarization and vertical polarization signal respectively. Part of the hardware for the above process is shown in left part of Figure 5.

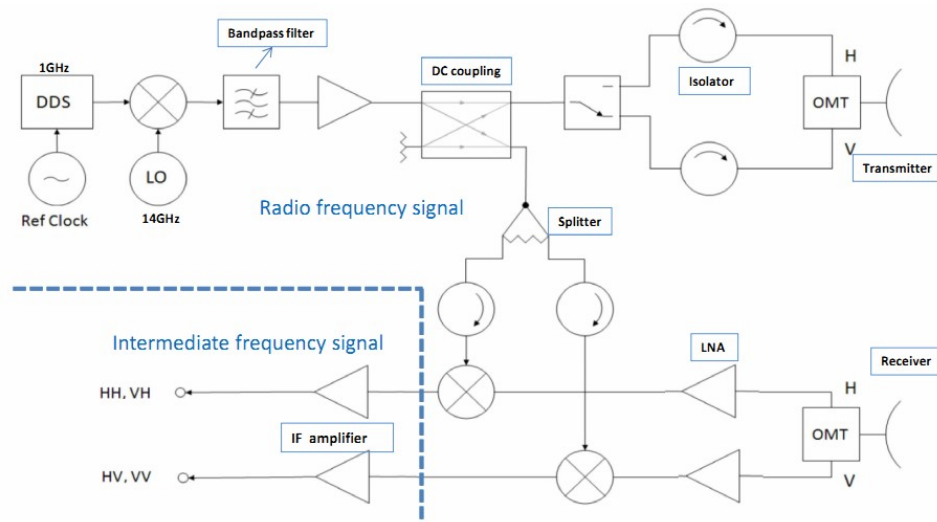


Figure 4: Dual antenna block diagram of TomoRadar microwave unit

In receiver part, the backscattered echo signals from targets are collected in both two polarization modes. Afterwards, the process is similar for each mode. The collected backscattered signal is amplified by the Low Noise Amplifier (LNA) first and then mixed with the frequency modulated transmitted signal. The result will be signal with Intermediate frequency (IF) of target. For the targets at various ranges the IFs of backscattered signal are distinct. After being amplified by the Auto IF amplifier (distance corrector), signal is finally collected and recorded. Besides above mentioned components, isolators have been applied to prevent the inner oscillations caused by those Radio Frequency (RF) part. In addition, the isolators help produce low Voltage Standing Wave Ratio (VSWR). Partly hardware of receiver part before IF amplifier can be viewed in right diagram of Figure 5.



Figure 5: Hardware of TomoRadar Radio part

3.4.1 DDS

DDS is a method of producing an analog waveform by generating a time-varying signal in digital form and then performing a digital-to-analog conversion [20]. Besides the advantages of broad tuning frequency bandwidth, low phase noise, the most important merit of DDS is the linearity of frequency sweep. However, DDS was not popular before when generating signal with wideband frequency even it was invented decades ago. The DDS output bandwidth development is limited by the power consumption and sweep frequency linearity. The wider the output bandwidth is, the higher the power consumption and the worse the sweep frequency linearity are [21]. Therefore, DDS mostly produces narrow band signal which cannot reach the application requirement. In our system, the generated signal bandwidth is 1 GHz which can be realized linearly by DDS.

As said before, the system modulation sweep frequency linearity affects system range resolution. When during modulation the frequency increases non-linearly the situation in Figure 6 will happen. This limitation is one critical problem in FM-CW radar system. Assume that the chirp change to be L_{in} and the instantly beat frequency change is $s = \frac{df_b}{dt}$. Then the chirp change can be present by [22].

$$L_{in} = \frac{S_{max} - S_{min}}{S_{min}}, \quad (14)$$

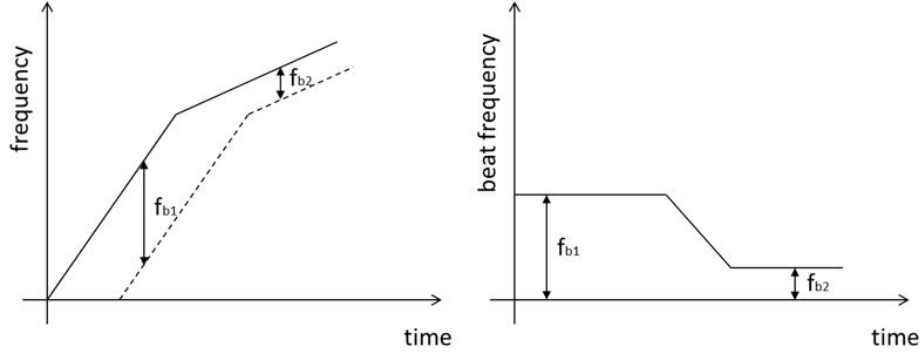


Figure 6: Effects of non-linearity in beat frequency

Considering non-linearized situation, system range resolution can be expressed as

$$\delta R = \sqrt{\left(\frac{c}{2B}\right)^2 + (R * L_{in})^2}, \quad (15)$$

Where c is light speed, B is bandwidth. It's obviously that only when L_{in} is small enough, which means the modulating frequency sweep is linear enough, can the range resolution be the smallest and stable value. In ideal case when the value of L_{in} is zero, range resolution is the best which is $c/2B$, and increasing frequency bandwidth will improve the range resolution. However, in normal situation, the linearity of sweep frequency plays an important role.

To obtain good system rang resolution, the modulation bandwidth is designed to be 1 GHz. However, through above analysis the non-linearity sweep frequency degrades range resolution. Comparing with other waveform generator, DDS waveform generator has super performance in linearity aspect in narrow band. Therefore, In TomoRadar DDS model AD9914/PCBZ which generates analog signal with frequencies up to 1 GHz is employed. Due to system independently, there is no common and simple way to check the sweep frequency linearity and the effects on TomoRadar. However, the linearity of system frequency sweep will be verified in the calibration process which is part of this thesis work.

Besides the good linearity performance in waveform generating, another merit of DDS is the easy module programming and construct process. Design of DDS is simplified with an evaluation Kit. There is a corresponding evaluation board of PLL with integrated VCO. By using control cable the evaluation board is connected with a USB interface board which is communicated with a laptop by USB cable. The frequency ramp should be programmed in advance in the DDS. From laptop, there is software helps adjust the parameters with simple operations in a graphical user interface. The DDS can be remote controlled and optimized.

3.4.2 Local oscillator

Local oscillator (LO) generates carrier signal which is used to convert the DDS output- IF band waveforms into RF band through the mixer. The carrier frequency

is 14 GHz, while after modulation the operating signal frequency is in the range of 13.5 GHz to 14.5 GHz.

3.4.3 DC coupling

As said in section 3.2, the received backscatter echo signal should be compared with the original transmitted signal to get the IF components from the backscatter signal. Therefore, part of the transmitted signal has been stripped before radiating and this process is done by the directional coupler (DC). As only the frequency of the signal used for mixing with received signal is critical, it doesn't matter about the signal amplitude. The directional coupler samples the transmitted signal by a constant power level, and mostly signal power is radiated. The real component can be seen in the left diagram in Figure 5.

3.4.4 Polarization Switch

Through Figure 4 it can be seen that there is only one PIN diode switch constructed in transmitter part before the signal radiation. When RF signal goes through the switch, it has been selected into one radiation polarization- horizontal or vertical. The PIN diode switch is synchronized with the FM waveform by a digitizer. Therefore, the switching frequency is controlled by digitizer and can be adjusted on digitizer control panel. In addition, the switch itself functions as an isolator whose isolation is around 55 dB, and it helps decrease the voltage ripple produced in the RF circuit.

In TomoRadar reception part, the receiver collected targets backscatter data in both two polarizations (H and V) at the same time. As said before, TomoRadar is a four channels ranging radar system. When TomoRadar works, the transmission polarization is changing between H and V automatically based on the preset converting frequency. However, the receiver is always working in two polarizations. Thus strictly to say, at one time there are two channels. The received data has same transmitted polarization but different receiving polarizations. Nevertheless, considering that the switching frequency is 100 samples, the modulation frequency is 163 Hz and the fly speed is around 10 meter/s; the fly test height is around 80 meters, and the antenna beam width is approximately 6 degrees. Thus the foot print is large. Above all, although the two radiation polarizations cannot work at the same time and transmit signal in order, the target areas where they collect backscatter echo data are mostly overlapped. In other words, mostly the same targets have been tested by both two different polarization signal. Consequently, TomoRadar is indeed a four channel ranging radar system.

There is a data log which records the radiation polarization switching situation. Through this switching log the received one channel data can be divided into two channels based on the transmission polarization. In this way, four channels data can be reconstructed. This channel dividing process is part of radar signal processing which will be given more details in chapter 6. The polarization modes switching can be controlled on digitizer panel which will be explained later in section 3.5, in addition, the received two channel signal forms can be checked in the same section.

3.4.5 Low Noise Amplifier

Normal amplifier amplifies both the useful signal and noise at the same time which decreases SNR a lot. While Low Noise Amplifier (LNA) amplifies the signal, but minimize the additional noise. Thus LNA amplifies signal but never degrade SNR much. Two LNAs are employed for the two receiver channels respectively. They can be seen in the right diagram in Figure 5. However, the LNA may cause saturation problem as some original strong signal has been amplified to be stronger.

3.4.6 Frequency Mixer

As said before, the splitter divides part of transmitted signal into two completely same parts to mix with backscattered signal in the corresponding mixer. Two mix branches are designed for two receive polarization modes. However, the signal mixing process and mathematic result models are same. Only one branch is explained to be an example.

In the mixer in receiver part, the transmitted signal is multiplied with the received signal, and then the output will be a low frequency signal consists of IF components of the targets. Via section 3.3, the transmitted signal and received backscatter signal can be expressed by equ.(6) and equ.(7). When these two signals mix in the mixer, the product of signals is

$$y(t) * y(t - T_p) = A_c \cos[\omega_c t + 2 * \pi * K \frac{t^2}{2}] * A_c \cos[\omega_c (t - T_p) + 2 * \pi * K \frac{(t - T_p)^2}{2}], \quad (16)$$

Through the trigonometric formula

$$\cos A \cdot \cos B = 0.5 * [\cos(A + B) + \cos(A - B)], \quad (17)$$

The result can be converted into

$$y_{mix} = \frac{A_c^2}{2} \cdot [\cos((2\omega_c - 2\pi K T_p) \cdot t + 2\pi K t^2 + (\frac{2\pi K}{2} T_p^2 - \omega_c T_p)) + \cos(2\pi K T_p \cdot t + (\omega_c T_p - \frac{2\pi K}{2} T_p^2))], \quad (18)$$

In equ.(18), the first cosine part consists a twice carrier frequency signal component, while the second cosine part contains a lower frequency component which is proportional to the target round time delay T_p . This frequency component is so called intermediate frequency which is the critical parameter when evaluating target range in equ.(9)

The first cosine part has been filtered out as the frequency exceeds cut-off frequency of the mixer, consequently, the mixer output only includes the signal with low frequency component. The output can be expressed as

$$y_{out} = \cos(2\pi K T_p \cdot t + (\omega_c T_p - \frac{2\pi K}{2} T_p^2)), \quad (19)$$

The mixer output will be sent to an amplifier which only modifies gain of signals for better final observe result. The mixer used in TomoRadar is ZX05-153+ which is made by Mini-circuit.

3.4.7 Intermediate frequency amplifier

An amplifier whose gain changes as the target distance varies is designed to improve the backscatter signal intensity but avoid saturation. It's well known that the intensity of backscatter microwave signal degrades as the target distance increases. With normal amplifier all the signals have been amplified by same gain, in this case, the interferences from short range objects maybe too strong and affect the recognition of expected target backscatter signal which locates in long range. Thus the amplifier is designed as a distance corrector to avoid above problem. With this distance corrector the signal with small frequency will be amplified by a small gain, while the signal with higher frequency will be amplified with bigger gain. In other words, the gain of this intermediate frequency amplifier grows 20 dB as the signal frequency increases ten times. The ideal working curve of IF amplifier is shown in Figure 7. Nevertheless, the real situation cannot reach ideal case, to achieve better system performance the intensity difference caused by IF amplifier is calibrated. This is part of system power calibration which will be explained in more details in section 5.2.

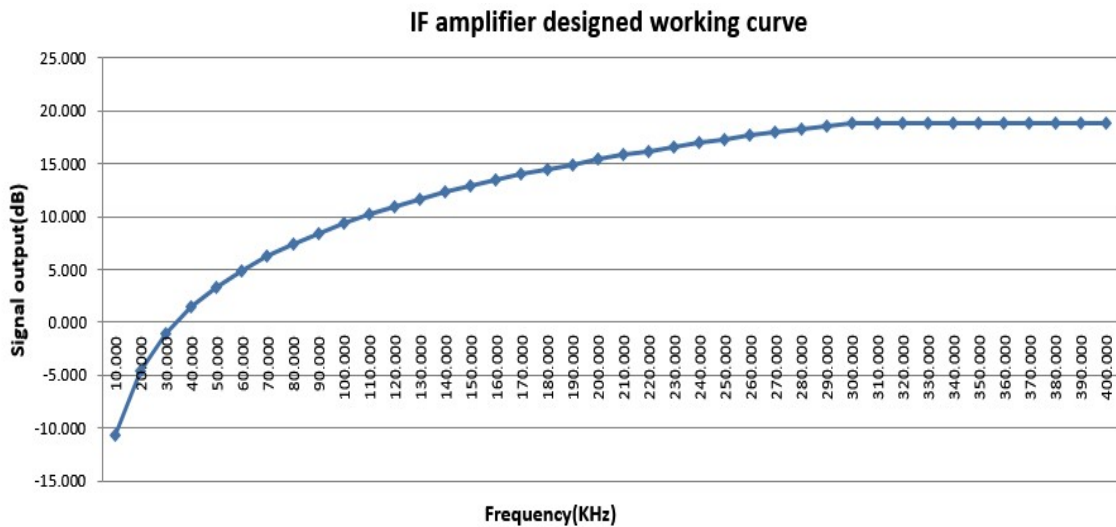


Figure 7: IF amplifier ideal working property

3.4.8 Antenna

Through the analysis in section 3.2, Ku-band is selected to be the operating band and the center frequency is 14 GHz. Above, a parabolic dish antenna with 12.0 to 16.0 frequency range is selected. Based on TomoRadar current setup, it is possible to reconfigure the operating frequency to be in the antenna frequency range by changing dedicated LO and corresponding band-pass filter.

For each antenna the net weight is around 0.9 Kg, while the dish diameter is around 33 cm. The antenna shape can be viewed in Figure 2. Each antenna has dual linear polarizations which is critical when constructing four channels system. In addition, the theoretical antenna gain is typically 24 dB. However, the antenna

gain fluctuates as frequency varies. The details of antenna gain is shown in Figure 8. This will be considered more in future power calibration task.

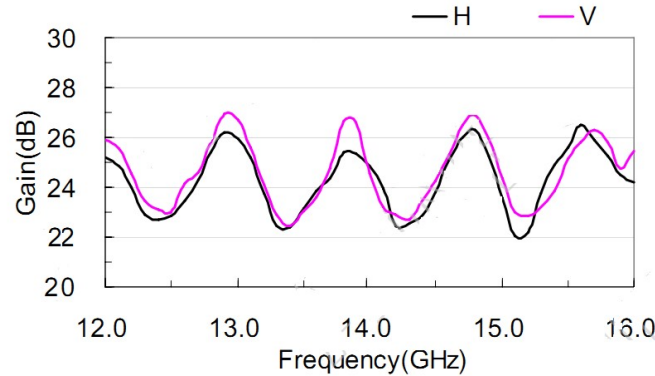


Figure 8: TomoRadar antenna gain

The antenna beam pattern is shown in Figure 9, it can be seen that the response from side lobe is low enough to prevent undesired echoes caused by side lobe. This property is critical to keep noise in accepted level.

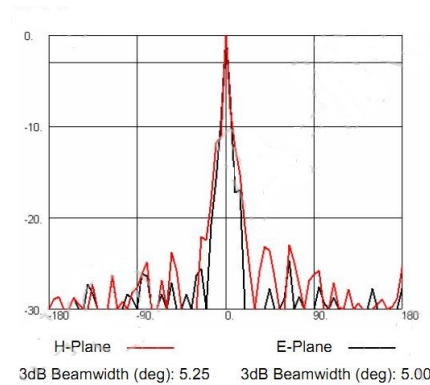


Figure 9: Antenna beam pattern

Two antennas are used for transmitter and receiver respectively. This is done to achieve great isolation between transmission and reception, and then prevent the effect from the transmitter signal leakage into receiver.

3.5 Data acquisition

As said before, TomoRadar adopts a National Instrument (NI) PXie- 6115 as a digitizer, which samples the amplified intermediate frequency backscatter signal waveforms at a fixed sampling frequency 2,5 MSample/second. Figure 10 demonstrates the digitizer (right corner) and the display. When TomoRadar works the displayed is used for the real time observing of the probe situation.

The DDS device is synchronized with digitizer by outputting a transistor–transistor logic (TTL) trigger signal. After receiving the trigger signal, digitizer samples after

ignoring the first 100 samples. This is done on the purpose of avoiding turn around effect which lowers signal noise ratio. The amount of Ignored samples is set to be 100 to guarantee enough samples for afterwards analog digital (A/D) conversion, on the other hand, compared with the total samples 7500 in one single modulation slope, 100 is such small amount that can be ignored when evaluating range resolution. The effective bandwidth in TomoRadar is assumed to be the whole band based on previous settings.

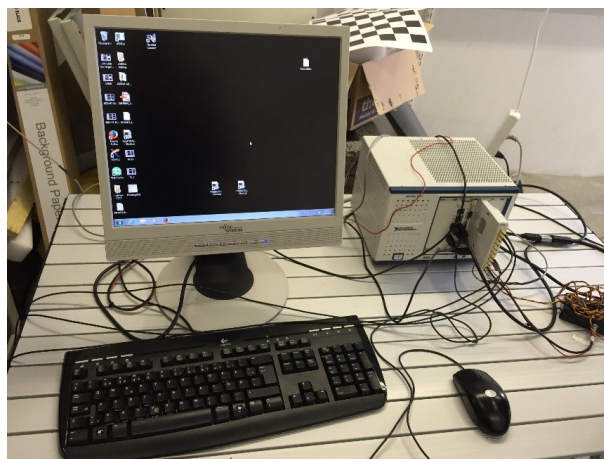


Figure 10: Digitizer and the display

A/D conversion is performed in the digitizer through pre-programming. The collected signal is presented by digitizer in both time and frequency domain. The real time sampling and demonstration facilitate the operator to monitor radar working status during the operation. In addition, the digitizer can control the transmitting polarization mode for different research purposes. During system operating period, the receiver always collects signal in two different channels at the same time, while with the control panel transmit channels switching frequency can be changed. Furthermore, all raw data is saved in the files which can be recognized and post-processed for forestry inventory research. Figure 11 shows how the digitizer is used and what can be observed.

3.6 Georeference

TomoRadar adopt a Novatel tightly coupled GNSS-IMU system as georeference solution. The employed FlexPak6 GNSS (Global Navigation Satellite System) receiver and the LCI tactical-grade IMU (Inertial Measurement Units) can offer centimeter level accuracy trajectory for airborne radar measurement. The DDS device triggers the georeference system with a TTL pulse. After receiving trigger signal, the integrated receiver unit records parameters related with fly track including the airborne platform global coordinate, velocity and altitude, etc. in global coordinated system. TomoRadar equips with the georeference system during the helicopter flying test. The recorded position data is analyzed and utilized with DEM (Digital Elevation Model) data to verify system calibration result.

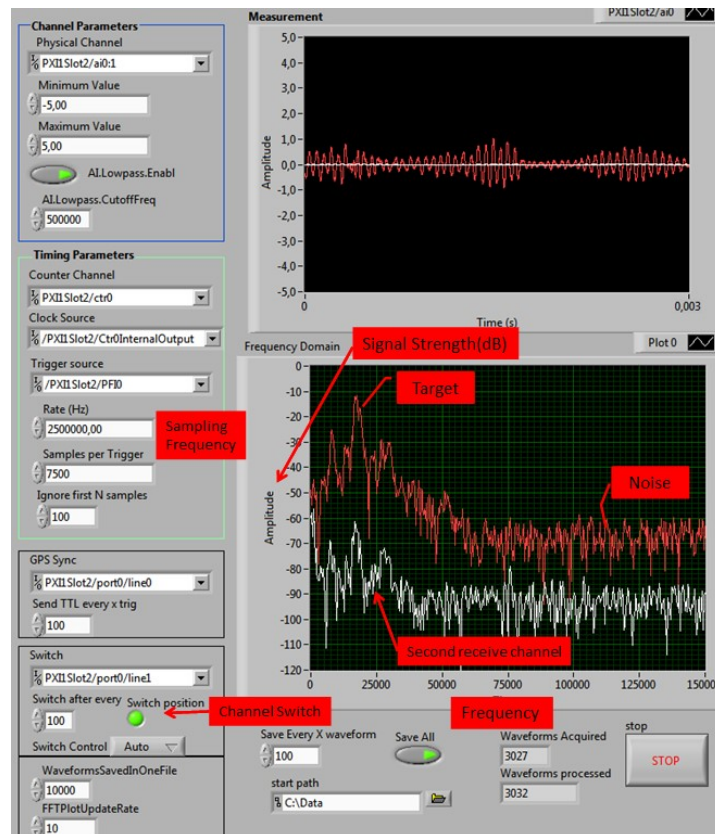


Figure 11: Display on digitizer

3.7 System frame

As TomoRadar system is helicopter/ UAV based ranging system, the total weight of the whole radar system should be as light as possible and the size should be small. For TomoRadar system, there are four parts. Two antennas for the transmitter and receiver respectively, and two metal boxes hold all the electronic components. These four parts are fixed together on one metal platform. The left diagram in Figure 12 presents the overview of the whole TomoRadar system. While in Figure 2, TomoRadar is fixed with frame and standing on the ground. This is the system frame when the system calibration ground test is carried. When testing the system in ground forest, the whole system is fixed on a car. The car went slowly in the forest and the system did test. The system on the car is shown in Figure 13. While when the helicopter fly test is carried, the whole system is fixed at one corner of the helicopter. The right diagram in Figure 12 presents how the system is installed on helicopter. The GPS and IMU are integrated with the system together.

As discussed in section 3.4.8 there is transmitter leakage which may go to the receiver and cause receiver saturation. To avoid this problem, two antennas are employed to maintain transmit- receive isolation level. However, the transmitter leakage affects the ground echo measurement as well. The relation between the



Figure 12: TomoRadar system



Figure 13: TomoRadar system fixed on car

leakage and echo signal beat frequency is

$$\frac{f_b}{f_{bl}} = \frac{R_g}{r_l}, \quad (20)$$

In which, f_b is the ground echo beat frequency, f_{bl} is the leakage signal beat frequency, R_g is the system altitude (range to ground), and r_l is the leakage path length. When the transmitter leakage is constantly, it's obviously that the shorter the leakage path length r_l is, the more intensity the ground echo has. Consequently, the cable in system radio part should be short. Check the shape of TomoRadar system in left diagram of Figure 12, it can be seen that the radio length of the cables used between antennas and radio part circuit is short.

4 System Range Resolution Study

System range resolution is defined to be the minimum range between two targets that the targets can be resolved respectively. Figure 14 presents the frequency spectrum sketches of returned signals from targets with different ranges. As shown in (a), when the range between two targets is big enough, they can be recognized easily, however, as the range between two targets decreases, the peaks of two targets returned signal frequency spectrum get closer which is shown in (b) and (c). When the range between two targets gets to the threshold value, the targets are still visible but nearly merged completely. If the range below the threshold value, then the two returned signals would be merged together which is shown in (d). This threshold value is the radar system range resolution.

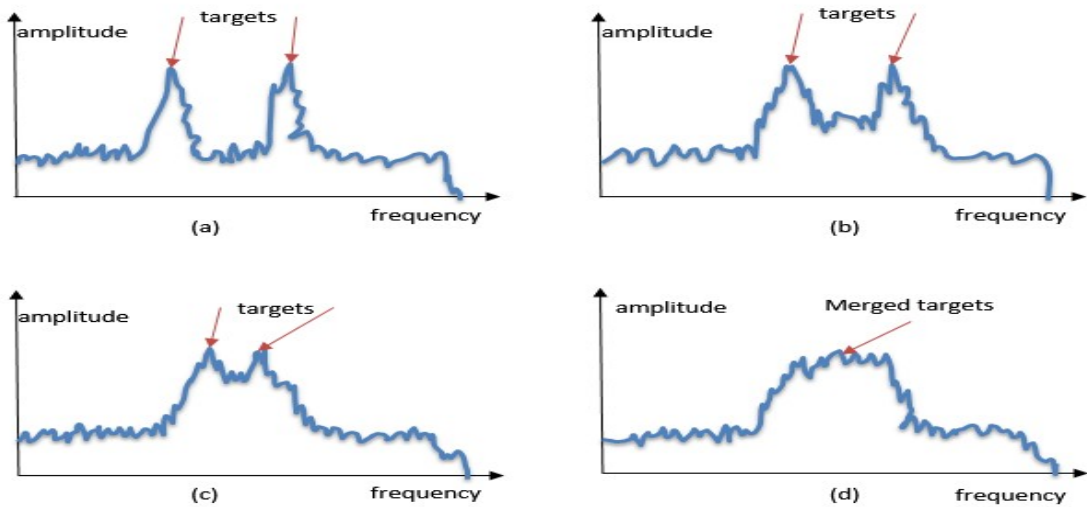


Figure 14: Different situation of two targets return signals

As analyzed in section 3.3, the range resolution can be calculated through equ.(13) and the theoretical value is 0.15 meter. However, there are variety factors affect the real range resolution, especially the linearity of system frequency increasing. Consequently, some experiments for both one target and two targets have been done to research the system range resolution.

4.1 Single target range resolution research experiment

4.1.1 Experiment process

To guarantee the target backscatter signal is strong enough, metal sheet has been chosen to be the target. All the equipment is arranged as Figure 1 shows except the georeference system which is not adopt in system ground test. Both the target and TomoRadar system arrangement can be seen from Figure 15. Left part of Figure 15 shows the metal target which is cut into square shape. In addition, there is metal support on one side of the target. While the right part of the diagram presents TomoRadar system. The real time scan results can be read from the display.

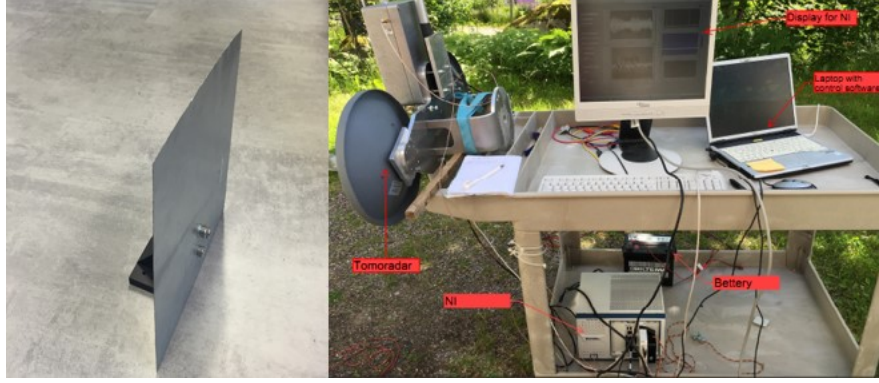


Figure 15: Range resolution research equipment

The general idea is to move the target every 0.15 meter and record the corresponding backscatter signals. Afterwards, compare the record values to verify if the target movements can be figured out from the TomoRadar system scan results. Theoretically, the target range resolution should be same no matter how far it is away from radar system within the radar work range. However, the experiment was conducted in three different positions. This design is not only to gain more accurate results from repeated experiments, but also because of TomoRadar system feature. As in TomoRadar system, the backscattered signals from targets located in far range will be amplified with larger gain than which from near targets, the distance from target to radar may affect the experiment results.

The metal sheet is put on a wood-made go-cart to make the moving easier. Compare with metal, wood has lower reflect coefficient which means the go-cart produces less interference. In addition, a soft tape is applied to draw a straight line from radar system to the go-cart. When the experiment is carried, the go cart is moved along the straight line to avoid extra effect from signal radiation direction changes. The experiment environment can be seen from Figure 16. TomoRadar system locates in the right lower part of Figure 16. The other end of the tape in the figure is target and go-cart. As the length of the go-cart surface is a little less than one meter, the metal sheet was designed to be moved four times in total towards one direction in each position.

4.1.2 Results and analysis

As designed before, the same measurements were carried in three different positions, the results are listed in Table 3.

The measurement results demonstrate that in short range wherever the target is, when the target moves 0.15 meters (some move distances are not exact 0.15m, the deviation is $\pm 0.03\text{m}$), the intermediate frequency of target backscatter signal changes regularly. The frequency changes are big enough to be recognized and the target ranges can be resolved from the corresponding intermediate frequencies. On one hand, the result proved the range resolution works with single target, on the other hand, through the increased frequency amount it can be seen that the



Figure 16: One target resolution verification experiment

Table 3: Single target range resolution verification

	Backscatter signal frequency (KHz)	Distance from radar to target (m)	Frequency difference with former recording(Hz)
A	58.2	26.062	-
	58.0	25.921	200
	57.5	25.746	500
	57.2	25.598	300
B	46.5	20.704	-
	46.2	20.545	300
	45.9	20.397	300
	45.5	20.260	400
C	24.3	10.476	-
	24.0	10.321	300
	23.6	10.157	400
	23.3	10.016	300

target backscatter signal intermediate frequency is proportional to the target range. However, the proportional relationship is already theoretically analyzed in equ.(10).

As analyzed before, only when the frequency increasing in modulating signal is linearly can the range resolution reaches theoretical value. Therefore, the measurement results proved that the modulating signal frequency increases linearly in short range.

4.2 Two Targets range resolution research experiment

4.2.1 Experiment process

When there are two targets locate close, the situation is different from when there is single target, as the backscattered signals of two targets will affect each other.

Through this experiment, the range resolution 0.15m will be verified to see if it works when the backscatter signals mix together.

Two metal sheets were employed which is shown in Figure 17. The metal sheet in rectangle shape is fixed at the end of the wood board. The other one is made in square shape. With different size, the backscattered signal from bigger metal sheet will not be blocked by the smaller one. On the board, there was scale marked on the white paper to help present the distance between two metal sheets. The smaller metal sheet is movable. When conducting the experiment, at each test position, the smaller metal sheet was moved to change the distance to the bigger one. As it was not sure when the two backscattered signals would be merged together, the start distance between two targets was set as 0.5m, then the distance between two targets decrease until the two corresponding backscattered signals merge together. The backscattered signals were present on the display and recorded. Similar with previous experiment, three different positions were selected to for the verification.



Figure 17: Two targets range resolution verification

4.2.2 Results and analysis

During the experiments, the related variables and results were recorded. When the two targets cannot be resolved respectively, the merged backscattered signal frequency spectrum was described. The results were presented in Table 4.

Through Table 4, it is obviously that when there are two targets near each other, it is difficult to reach the theoretical range resolution value. When the distance is 0.5 meters, no matter how far away the targets are from radar, they can be resolved easily. However, when the distance decreased to be 0.3 meters, whether the targets ranges can be figured out depends on the targets position. As shown in Figure 16, there were trees around the test field which produced interference backscattered signal. The trees didn't distribute evenly, therefore, the effect amount from trees backscattered signals were related with the target positions. From the experiment results, only when targets locate around 20 meters away from radar system, can the targets can be resolved respectively. In the other two test positions, the backscattered signals from two targets merge together which is similar with the last diagram in Figure 14.

Table 4: Two targets range resolution verification results

	Backscattered signal frequency-smaller sheet(KHz)	Backscattered signal frequency-bigger sheet(KHz)	Distance between smaller sheet radar(m)	Distance between two metal sheets (cm)
A	23.4	24.3	10.04	50
	23.6	Two peaks merge	10.235	30
B	44	45.1	19.578	50
	44.4	45.1	19.777	30
	44.3 45.4 , two peaks merge together, only a wide pulse		19.879	20
	44.6 45.3, signal frequency spectrums is not stable, sometimes merge and sometimes separate		19.928	15
C	60.3	61.4	27.044	50
	Two peaks merge together		27.243	30

However, if focused on the test position B which is around 20 meters away from radar, it can be found that when distance between two targets is less than 0.3 meters, there were different phenomenon. When the distance decreased to be 0.15 meters, the targets can be resolved respectively. It can be assumed that if the environment was purity without any interference, the theoretical range resolution value can be reached.

One thing has to be mentioned, that even though we have utilized the wood cart as a platform to carry the metal sheet target, the wood structure of the cart frame still reflect the transmitted RF signal which might expend the width of target in frequency domain which results in that two targets could not be recognized after FFT. Therefore, reflected signals from go-cart, around trees, even the floor, all affect the experiment results accuracy.

What's more, field test range was another limitation for the range resolution verification experiments. Through this experiment, only the situation in short range can be referred. How the system range resolution works in real helicopter fly test is unknown. Thus the test range add inaccuracies of the system range resolution study results. This rang resolution study was carried for the first version of TomoRadar, until this moment, TomoRadar has been upgrade twice and the backscattered signal noise ratio is improved. Theoretically, the range resolution should be better in upgraded system.

5 System Calibration and Uncertainty

All measurement instruments require calibration before putting in real application. In TomoRadar, as the system is developed for forest investigation, and the scan results will be analyzed to evaluate the variables around forest, e.g. tree height, density, etc., it is especially critical to find precise relation between intermediate frequency of target backscatter echo signal and the target range. Besides, the power of echo signal needs to be calibrated as well. This chapter discusses the TomoRadar system calibration.

5.1 Range calibration

5.1.1 Range calibration method

Through section 3.3 it can be known that the relation between backscatter signal intermediate frequency and the target range is linear. What's more, through the parameters listed in Table 2 the exactly relation between f_{if} and R can be expressed as $f_{if}=2.173*R$. However, it is not sure that whether this theoretically relation is accurate enough for the system. Consequently, the range calibration was conducted to correct the systematic errors and get the exactly relationship between f_{if} and R.

Based on the linear relationship, the range calibration is designed to probe a target at different positions by TomoRadar and record the target backscatter waveform intermediate frequencies. In addition, the real distance between target and TomoRadar is measured as ground truth data and then compared with the derived target range from frequency. Eventually, calibrated linear model is figured out.

Different from range resolution study experiment, Luneburg lens is used as experiment target. Luneburg lens is a sphere whose shell contains considerable dielectric. It is a perfect radar reflector when the surface has been partly metalized. The advantage of utilizing Luneburg lens as a reflector is that it can reflect the waveform back to radar with least possible scattering. With this property the backscatter waveform strength can be strong enough to reduce the noise effect caused by experiment around environment. The lens with 30 cm diameter and 45m² Radio Cross Section (RCS) at frequency of 9.375 GHz was utilized in our calibration process. However, the RCS of Luneburg changes based on f^2 rule when the system working frequency changes. In detail, the rule is

$$\left(\frac{f_2}{f_0}\right)^2 = \frac{RCS_2}{RCS_0}, \quad (21)$$

In our system, as the central frequency is 14 GHz the RCS becomes to be 100.35 m² which is 20 dBm².

In the calibration process, the Luneburg lens is put on the go-cart. A tape is still fixed between radar and target to generate a straightly moving path. When the experiment is conducting, target is moved along the tape regularly and the real distance between target and radar is measured by laser range finder.

In more details, the lens was moved from 10 meters away from radar to 40 meters. During the moving process, the intermediate frequency of target backscatter signal

from the digitizer was recorded every one meter. Through repeating the measurement at different ranges the effect of multipath propagation was lessened [23]. Figure 18 presents calibration process arrangement. The range calibration is conducted on the ground outside of FGI where there are a lot of interference objects, e.g. trees, cars, etc. The backscattered signals produced by the go-cart, trees and ground are treated as noise in the experiment. Figure 19 demonstrates the real experiment arrangement and surroundings.

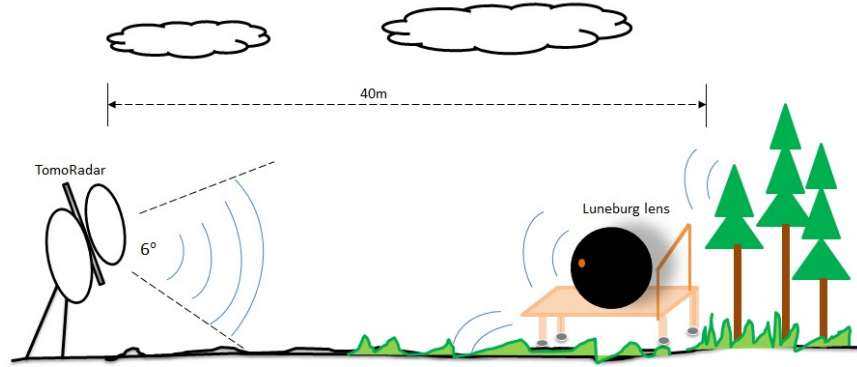


Figure 18: TomoRadar range calibration experiment sketch



Figure 19: TomoRadar range calibration

5.1.2 Range calibration result

As TomoRadar upgrades there are three versions have been tested. The calibration was done every time before airborne fly test. Hence, the range calibration process has been repeated three times in different time. The process is same while the test range is slightly different. All the calibration experiment results are listed in Table 5.

To find the exactly relation between target range and backscatter signal frequency, the conventional least squares solution was adopted to fit the tested data. As theoretically there relation should be linear. The fitting line is generated based on linear relationship regulations. The coefficient of determination which is denoted as R^2 is

Table 5: Range calibration results

7,7,2015		19,10,2015		27,11,2015	
Range (m)	Frequency(KHz)	Range(m)	Frequency(KHz)	Range(m)	Frequency(KHz)
10.016	23.3	14.841	32.7	10,069	24,4
10.157	23.6	15.335	33.7	11,077	26,6
10.321	24	15.785	35	12,034	28,5
10.479	24.3			20,05	46
20.26	45.5	24.953	53.3	21,053	48,3
20.397	45.9	25.39	54.3	23,051	52,7
20.545	46.2	25.912	55.5	30,031	67,65
20.704	46.5			30,967	69,8
25.598	57.2	35	73.6	31,982	72
25.746	57.5	35.5	73.65	37,93	85
25.921	58	36	75.7	39,034	87,3
26.062	58.2			40,015	89,4

used to obtain the fitting relations. Assume \bar{y} is the mean value of the data set, the total sum of squares is present by SS_{tot} and then the sum of squares of residuals is SS_{res} . They can be obtained by the equations that

$$SS_{tot} = \sum_i (y_i - \bar{y})^2, \quad (22)$$

$$SS_{res} = \sum_i (y_i - f_i)^2, \quad (23)$$

In which, y_i is the values in the original data set, and f_i is the predict value from the fitting model.

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}}, \quad (24)$$

The value of R^2 presents the correlation between the original data set and the fitting data model. If R^2 was 1, it indicates that the fitting model fits the original data well, if it was 0, it means the line doesn't fit original data at all. The calibrated data will be fit together and checked by R^2 regulations.

After fitting the original data, Figure 20 presents the fitting results for the whole three calibrations. Through both the line shape and the R^2 value, it can be seen that the relation between target range and backscatter signal intermediate frequency is linear which fulfils the principle of TomoRadar system. The equation parameters vary a little because of TomoRadar hardware upgrading.

The analysis for every calibration experiment is same, thus only the data measured on 27th,NOV,2015 is discussed more in following chapter as an example. It is the last calibration experiment which is conducted for the newest version of TomoRadar.

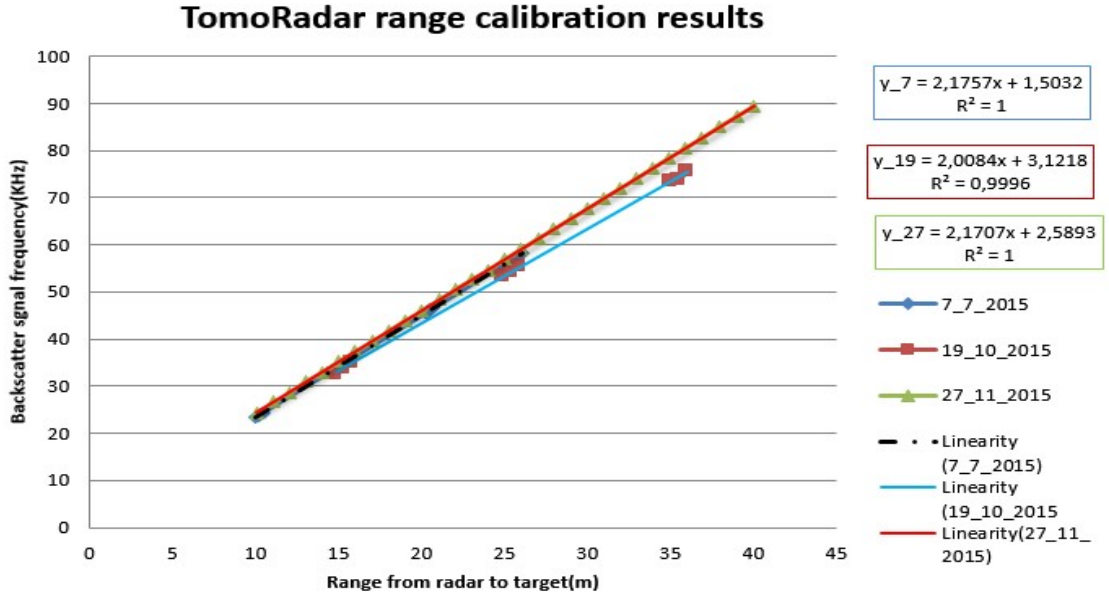


Figure 20: TomoRadar range calibration experiment results

With the help of fitting line, the accurate range conversion equation can be expressed as

$$f_{if} = 2.1707 * R + 2.5893, \quad (25)$$

In which, f_{if} and 2.5893 have the unit of KHz. With R^2 value be 1 which means the fitting line can predict the original data accurately. From equ.(22) the range converting equation can be derived to

$$R = \frac{f_{if} - 2.5893}{2.1707}, \quad (26)$$

In which, R is the range with unit of meter, and the unit of f_{if} in equ.(25) is KHz. With the utilization of equ.(26) the target range can be evaluated accurately. Moreover, the stand profile of scanned area can be drawn and researched with these evaluated range information. As TomoRadar is a ranging radar which aims to invest the forest by evaluating tree height, species, volume, etc., the range conversion equation is such import for it affects the final forest inventory results. Range estimation with the equation is done in signal processing part with Matlab which can be referred in Appendix.

Considering the importance of range estimation parameters, in addition, as discussed before the range calibration is done in short range which may not apply for the TomoRadar designed range 10 to 150 meters, it is necessary to verify the calibration result.

As said before, this range calibration method can be used to verify the system frequency modulation linearity as well. While the range equation can be expressed by

$$f_{if} = \frac{2R * S}{c}, \quad (27)$$

S is beat frequency changes. Through the analysis, the linearity of frequency modulation sweep is critical for ranging radar range resolution. From equ.(24), it is obviously that one way to verify the linearity of modulation sweep is to make sure about the exactly relation between the target range and backscatter signal intermediate frequency, which is the purpose of range calibration.

5.2 Power calibration

Power calibration is more complicated than range calibration as there is not only propagation loss, but also system consumption. Moreover, there are three different kinds of amplifiers which are described in section 3.4. On the other hand, even the received power and the real distance between target and radar has been figured out with instruments, there is no efficiency method to verify the power calibration result.

However, at this moment, the performance of IF amplifier has been calibrated. The ideal performance of IF amplifier is demonstrated in section 3.4.7. When system runs, the increasing trend of the gain cannot reach the ideal case. Thus partly power calibration can be done by completing the power compensation on IF amplifier.

The real performance of IF amplifier is researched first. A 100mv signal was adopt as the amplifier model input, afterwards, the outputs of the IF amplifier over the frequency range from 10 KHz to 1GHz are measured and recorded. The input signal frequency changed every ten kilo hertz until reached the maximum value. Partly test results have been shown in Table 6.

Table 6: IF amplifier output amplitude test

Frequency(KHz)	Amplitude(dBV)	Frequency(KHz)	Amplitude(dBV)
10	-10.633	170	11.732
30	-0.724	190	12.256
50	3.522	210	12.629
70	6.235	230	12.829
90	8.131	250	13.026
110	9.426	270	13.179
130	10.630	290	13.293
150	11.174	300	13.293

Eventually, the measured values have been compared with the ideal line to figure out the amplifier different consequents between real performance and the ideal design case and produce the amount of power compensation. When evaluating the scanned stand profile the power compensation is added to the amplitude of intermediate frequency components. All the measured data is compared with the designed values which are shown in Figure 21. As the radar system required design maximum measure range is 100 meter which means the received possible maximum target backscatter

signal frequency is around 220 KHz, the maximum researched input signal frequency is chosen to be 300 KHz with 80 KHz frequency margin.

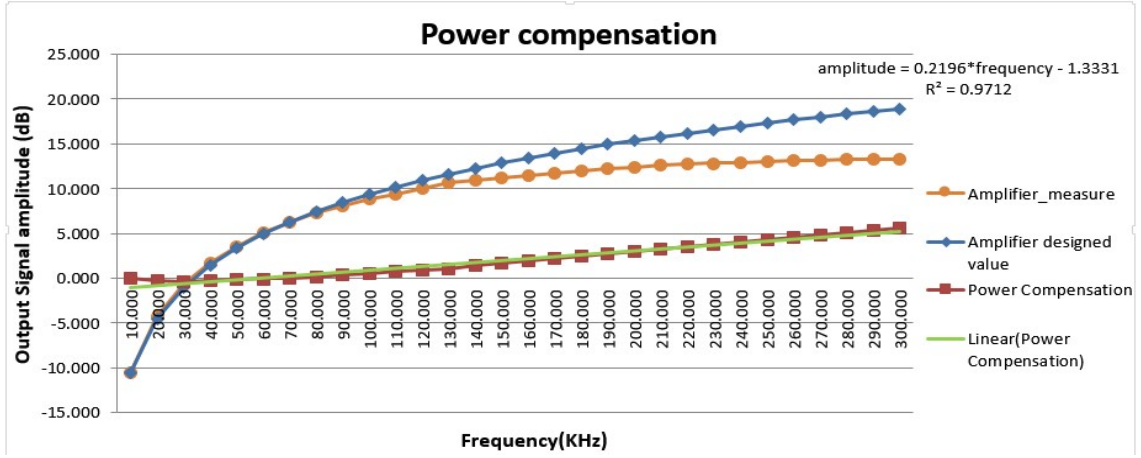


Figure 21: Amplifier feature study

Through Figure 21 it is obviously that the gain of IF amplifier doesn't increase as designed rules in high frequency range. The amplifier performance cannot reach ideal expectation. Moreover, the difference between real amplify gains and designed values increases as frequency grows above around 150 KHz. However, the difference has been figured out and fitting to be a line which is treated as the power compensation criteria. The fitting process was accomplished based on the R2 rules which is described in section 5.1.1. In this version, the R^2 value of the fitting line is 0.9712 which means the fitting line can predict the expected data with high accuracy.

The power compensation is done based on the pre-studied power compensation fitting equation. The process is presented in the signal processing which can be referred in the appendix. In future, the power calibration will be studied further from the whole system view. Based on the principle of microwave propagation [24], the relation between target distance and backscatter signal power can be expressed as

$$R^4 = \frac{\lambda^2 G^2 P_t G_a G_{if} \sigma}{(4\pi)^3} * \frac{1}{P_r}, \quad (28)$$

Where R is the range between radar and target, G is the antenna gain and G_a is the system normal amplifier gain; G_{if} is the IF amplifier gain; σ is the RCS of target; λ is wavelength of signal, while P_t and P_r are the transmitted power and received power.

In equ.28, the variables λ , G , G_a , P_t , σ are constants whose product can be assumed to be a coefficient C. This assumption can be expressed as

$$P_r = C * \frac{G_{if}}{R^4}, \quad (29)$$

In which, G_{if} varies as the range changes as analyzed before. The property of IF amplifier is already studied and the theoretical gain is known when target locates at

certain range. However, to calibrate the system power level, the coefficient C can be remain to be unknown ,while the real time G_{if} and received power have to be measured. In this way, there is no need to make clear about the values of variables included in C .

Theoretically, the received target backscattered signal power should be proportional to the ratio of G_{if} and the fourth power of target range. The power calibration experiments can be designed similar with the range calibration process. Different from range calibration, in power calibration, other measured variables become to be the received backscattered signal power and the corresponding IF amplifier gain besides target real range. With these measured values, the relation between received signal power and range can be drawn.

In case the relation between the received targets backscattered signal power and the ratio of G_{if} and the fourth power of targets range is verified to be satisfied the proportional relation. The conclusion will be drawn that the calibration which is done on IF amplifier is enough for the system. If the relation was not the expected result, then the parameters including the system gain, antenna gain and target RCS in the coefficient C should be studied as well. In the second case, the calibration process would become to be more complicated. What's more, the standard values of received targets backscattered signal power needs to be defined. Consequently, the power calibration requires more work in future.

5.3 Other factors effects

Limited by the environment and system properties there are some factors affect the calibration results. From the calibration environment aspect, the calibration is designed and carried on ground. The environment is much different from TomoRadar real working situation. There are lots of interference from the around environment. Moreover, the area of test field on the ground is so limited that the maximum test range is only 40 meters. Therefore, the test field cannot guarantee the result works when the working situation changes.

When it comes to the calibration process itself, there are some problems. It's not known where the radar radiation start point can be. It is assumed that the start point is the center point between the two antenna dishes. In this situation, the range between target and radar can only be estimated. Therefore these factors may affect the calibration results. However, the calibration effect was checked in the helicopter flying test and presented in next chapter.

When the TomoRadar works on helicopter emitting continuous waves towards to the ground vertically, the helicopter flied along a straight line at a speed of about 10 m/s. In ideal case, the signal emission direction is always vertical and the helicopter has no variation along fly trajectory. The target range is over estimated as the radar position varies. However, as said before, the helicopter flying speed is around 10m/s, and the microwave transmit speed in the air is around $3 * 10^8$ m /s.The process can be referred in Figure 22 Considering the target range is 100 meter at maximum when conducting flying test over forest, the overestimated range amount is too small to affect the measured target range accuracy. When the target backscattered signal

reaches at the radar receiver, the helicopter can be seen that still at the original position. Therefore, this is not considered in the system calibration.

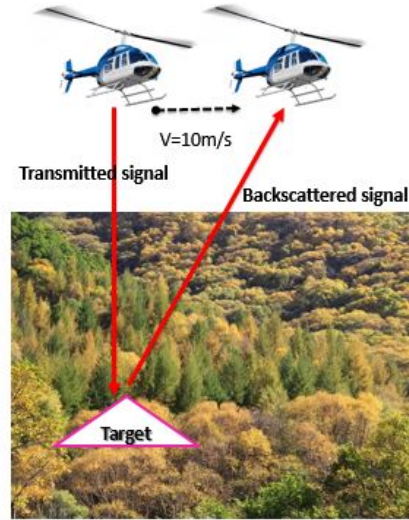


Figure 22: TomoRadar installation on helicopter

However, during the flying test the helicopter has body vibration phenomenon, especially when rising to higher altitude and turning direction. In this case, the radar incident angle cannot keep to be vertically towards the ground and the angle offset may lead to different range measurement results. However, this range variation could be retouched afterwards by importing the helicopter attitude data collected by IMU module.

Another concern factor introduced by the helicopter is the Micro-Doppler (MD) effect which is caused by helicopter's rotor blades. The rotating rotor blade is also a scatter which can lead to backscattered signals interacting with the echoes from targets [25]. As TomoRadar emits signal towards the ground directly, and the helicopter supporter and rotor blade are not within the signal transmission scope, there is little directly negative effects from them.

However, another possibility might happen to lead to the M-D effects which is shown in Figure 23. Through the experiments, it is well known that the ground produces strong backscattered signals. The backscattered signals are received by TomoRadar, nevertheless, the time domain reflection might happen when the ground backscattered signals reaches helicopter body or rotating rotor blade. Afterwards, the echoes from ground caused by the previous reflection signal reach at the radar receiver. In this case, the echoes whose intermediate frequency is around two times than the target echoes'. When more reflection happened, echoes with higher intermediate frequency may appear. During the test, helicopter worked at around 50 meters, therefore, the echo return time is so short that the reflected echoes will be mixed with target echoes in the radar receiver. As the transmitted signal is a wide band signal (1 GHz), when mixer doing autocorrelation the reflection echoes will lead to a different intermediate frequency component. What's more, the power of reflected

signals attenuated much during the transmission. Therefore it doesn't affect the target echoes recognition. More analysis will be introduced in chapter 6.

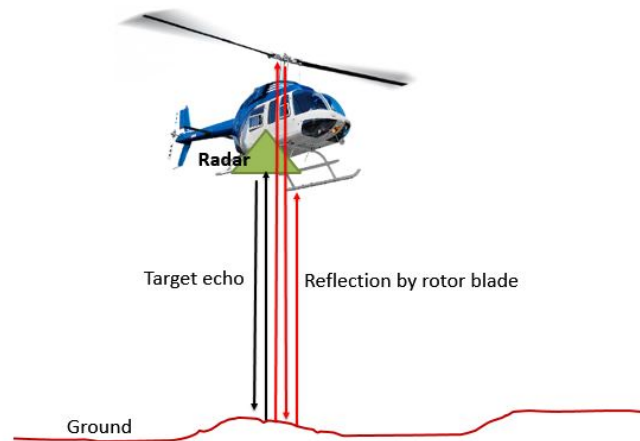


Figure 23: TomoRadar installation on helicopter

For the power calibration, strictly, it cannot to be seen as complete power calibration because of the lack of the whole system power inspection. The IF amplifier is only one ring of the system. At this moment, only some power compensation based on IF amplifier features has been done. However, when the IF amplifier works in the system, the input signal becomes to be more complex, and the performance might be different from working only with the outside circuit board. Therefore, it cannot be sure that whether the power compensation amount is right or not. At this moment, there is no good method to check the power calibration result. Hence, as analyzed before, more researches work about the different gains and power consuming in the system have to be done

6 System Measurements and signal processing

So far TomoRadar has been tested on helicopter for three times in Finland. One was carried over FGI, while the other two were carried over EVO. Every time after the testing, TomoRadar was upgraded depends on the system design requirements and previous testing results. Consequently, Three different TomoRadar versions in totally were tested. In this chapter, the TomoRadar helicopter based flying test signal processing and output are presented and discussed.

6.1 System performance measurement

The last helicopter borne fly test was introduced here as example. As said before, the third test was conducted in Evo, Finland. Evo is one test site locating in southern Finland and approximately 100 Km away from Helsinki (61°13' N, 25°6' E). It is part of southern Boreal Forest Zone. Tree species in this area are known to be mainly Scots pine, Norway spruce and birch. Evo has already been researched by Airborne Laser Scanner (ALS) produced in FGI and data on forest properties was recorded. Therefore the test result over same forest from TomoRadar can be compared with laser scanning data in future.

When doing fly test on 2nd, DEC, 2015, both the IMU/GNSS and the RF/IF part of TomoRadar were installed on a steel-made frame which is rigidly connected to an arm of a helicopter (Bell 206). How the TomoRadar was installed on helicopter can be viewed in Figure 24. It can be seen that the IF and RF parts were installed on the bottom of frame with the two antennas pointing toward to ground directly with 0 degree. The IMU unit was fixed above the radar system and GNSS was installed with the help of a mast. Through the installation figure, it is clearly that the GNSS signal might be partly blocked by the helicopter support frame. However, the processed position data presents that the negative effect can be ignored. All the staffs were arranged to make the communication cables as short as possible to avoid more noise. The cables were gathered into a bundle which is marked by a red circle in the right diagram in Figure 24 and inside helicopter cabin the cables were connected with different instruments.

As Figure 25 shows, the other data collecting related instruments were installed inside. When TomoRadar started to work, trigger signal was sent from DDS to the NI oscillator card and the probed area backscatter signal waveforms were recorded by the digitizer. The waveforms were real time processed and presented on the display for observation. The hardware parameters can be set from the laptop which is convenient when designing the system. However, when the flying test started, the preset parameters would not be changed.

Figure 26 presents how the helicopter based radar system works over the forest and the output model of scan results. The transmitter parabolic antenna sent signals with 6 degree beam width. The helicopter fly height was around 50 meters in third flying test. Therefore, the footprint was a round area with radius about 5 meters. The scanned results were presented by stand profiles which can be seen as cross sections of the forest. In the right corner, the diagram which is drawn by black



Figure 24: TomoRadar installation on helicopter

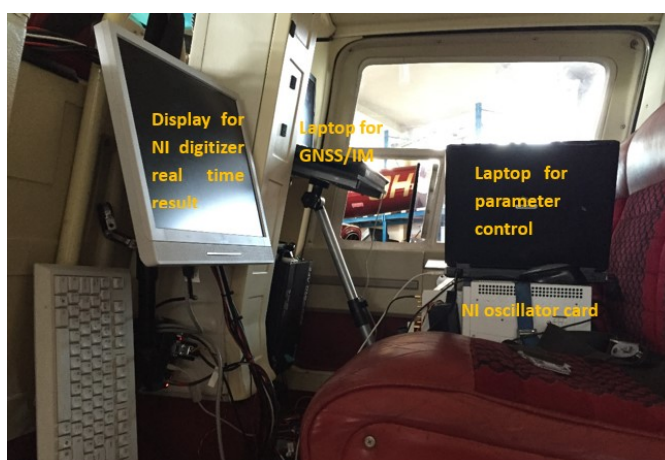


Figure 25: TomoRadar helicopter based test inside arrangement

line was the frequency spectrum of backscattered signal from one target. After the helicopter flew over the whole test areas, all the backscattered signals were collected, and then the scanned area could be reconstructed through the frequencies analysis of the backscattered signals. More details will be explained afterwards.

6.2 TomoRadar signal processing

Matlab is adopted to process the TomoRadar collected data for its powerful signal processing function. Figure 27 demonstrates the signal processing process with Matlab.

Through digitizer, the scanned microwave data was saved in files that each file consists of 10000 waveforms. In addition, the transmitter channel conversion logs were also recorded in text files. Afterwards, the data files were converted into binary files which can be read and processed by Matlab.

Before processing the data, the binary files were imported in Matlab with the

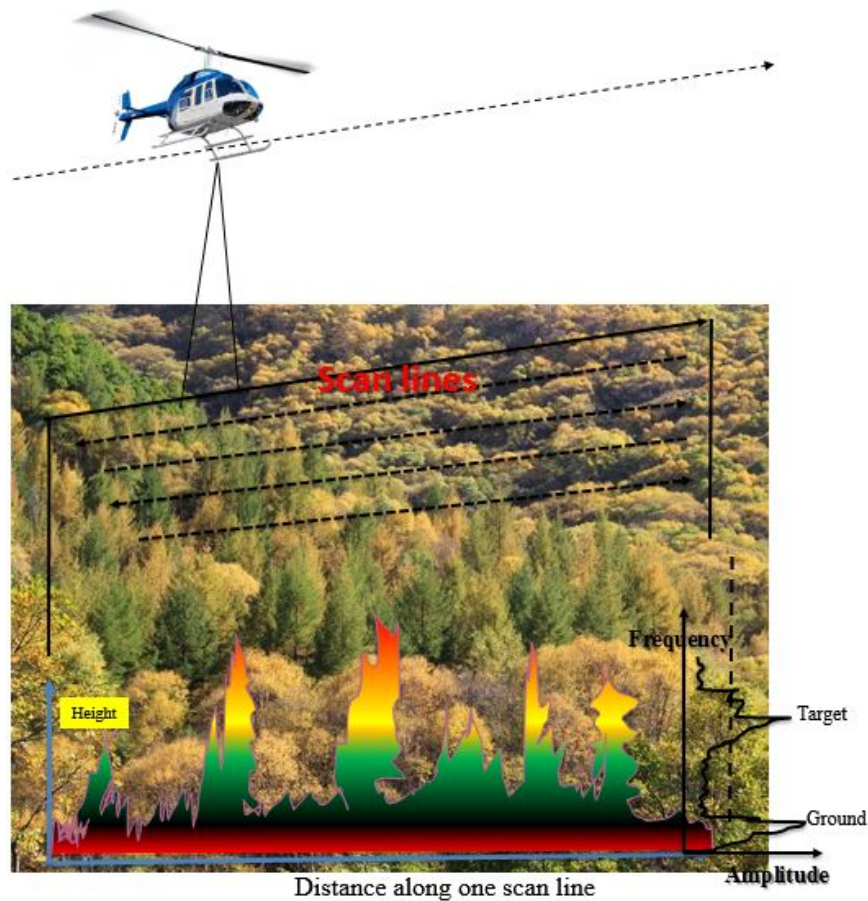


Figure 26: TomoRadar measurement principle

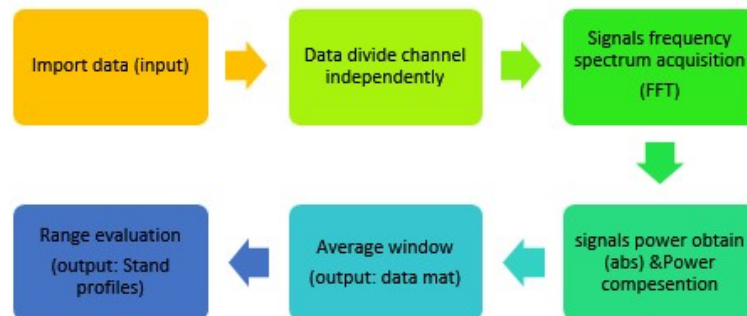


Figure 27: Signal Processing

function *'fread'*, while the transmit channel conversion index files were read by the function *'import'*. Eventually, all the data was saved in Matlab matrixes. Through the section 3.4.6, the data can be expressed by the equ.(19). which is

$$y_{out} = \cos(2\pi K T_p \cdot t + (\omega_c T_p - \frac{2\pi K}{2}(T_p)^2)),$$

As when digitizer saves the data, the data from two different receiver channels is saved independently at same time, they can be processed directly without dividing. While, the transmit channels are not divided. In other words, there are two data files for each data collecting process. Each data file contains data from both two transmit channels, but only for one receiver channel. In total, the data of four channels is recorded. This has been explained in section 3.4.4. Consequently, before further processing the import data with FFT function, one data file has to be divided into two parts for the two different transmit polarizations.

After dividing, the data from four channels was processed channels independently. The processes were same. Firstly, the data is converted from time domain to frequency domain with the Matlab function ‘*fft*’. With this step, the backscattered signal waveforms intermediate frequency can be obtained from equ.(19)

$$f_{if} = KT_p, \quad (30)$$

Assume the sweep frequency produced by DDS is linear enough, the frequency changing rate K should be constant and equal to the ratio of the total frequency band and the chirp time. Thus equ.(30) can be expressed with the sweep bandwidth and chirp time

$$f_{if} = \frac{B}{T_b}T_p, \quad (31)$$

As the round time delay T_p can be expressed by target range and light speed as $T_p = \frac{2R}{c}$, and through Figure 3 the chirp time T_b is $1/2f_{mod}$. Taking all these two formulars into equ.(31) the relation between target backscattered signal intermediate frequency and target range can be acquired

$$f_{if} = \frac{B}{1/2f_{mod}} \cdot \frac{2R}{c} = \frac{4Bf_{mod}R}{c}, \quad (32)$$

Compare equ.(32) and equ.(10), they are completely same results. Consequently, the relation between intermediate frequencies f_{if} and targets range R is exactly same from both mathematic analysis and the signal waveforms analysis.

After FFT processing, all the data was in frequency domain and the corresponding power was stored in order. Then the data is converted into decibel unit with the power compensation added together. The power compensation amount was pre-evaluated based on power calibration result as described in section 5.2.

Hereafter the data passed through an average filter to lower the noise level. In the designed filter, each data is the mean value of its forward and afterward continuous five data. This step degrades interference significantly. Until now, initial data processing has been done through above steps. The data can be taken to do other research task.

As TomoRadar is designed for forest inventory, frequencies are evaluated to target range based on the range calibration result. This is done in y axis when plotting the stand profile diagrams. As the data is already in the same frequency range with different amplitude, when plotting the data in frequency domain one waveform by one waveform, the corresponding frequency can be seen as range directly. The

amplitude of frequencies refers to the signal strength at certain frequency and it is presented by color in the stand profile diagram. To acquire better stand profile shape for observing, the x axis is set to be fly distance by assuming the fly speed to be 10 meter per second. Combined with the modulation frequency 163 waveforms per second, the width of one waveform is around 16.3 m.

Through this process the stand profiles of targets are obtained. With these profile diagrams, information around the forest can be estimated and researched. The stand profile diagrams present the tree height clearly. And the tree species can be evaluated from the stand profile shape. More useful forest information including trees distribution, forest density can be studied by TomoRadar scan results.

Partly results from three flying tests will be presented and discussed in the following sections. The Matlab code for the whole data process can be referred in the appendix part.

6.3 System measurement result analysis

Through the process described in last section, forest stand profiles were drawn. Figure 28 is one example from TomoRadar third flying test. The diagram contains one minute data. The colors in the diagram mean different signal power levels which can be referred in the color bar. In the figure, there is a yellow line locates around 60 meters. The yellow line is judged to be the ground, because of its height location and continuous present. Above the ground, the trees can be recognized through the targets shape. In some points, there were extra signal presented nearly in the whole range scale. Such kind of phenomenon was called saturation which was caused by the excessively strong backscattered signal power.

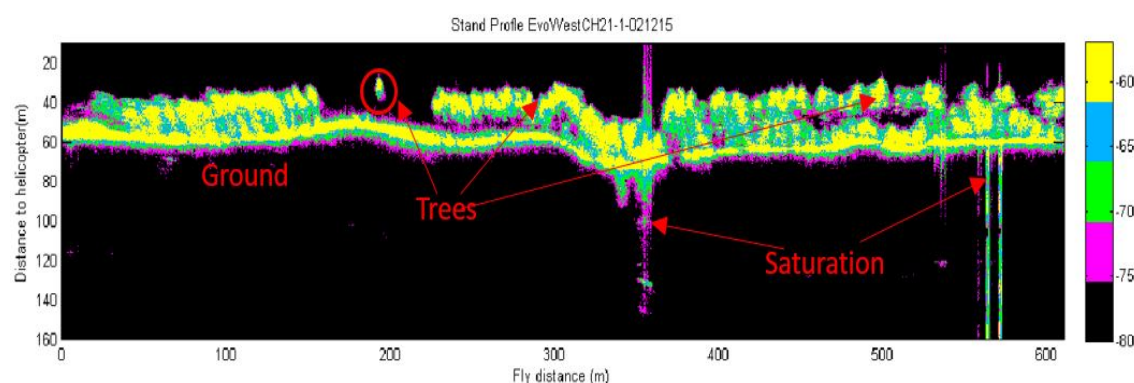


Figure 28: Stand profile of one minute data

In the upper diagram in Figure 29, one tree was zoom in and presented. The major tree canopy was presented by yellow color and the range was about from 28 meters to 34 meters. The ground was presented by yellow color as well for it stands for strong power signal. The distance between ground and radar was within the range from 50 meters to 55 meters. All these ranges were figured out through equ.(26) with the frequencies of backscattered signals. The lower diagram in Figure 29 demonstrates one backscattered waveform drawn in frequency domain. As shown

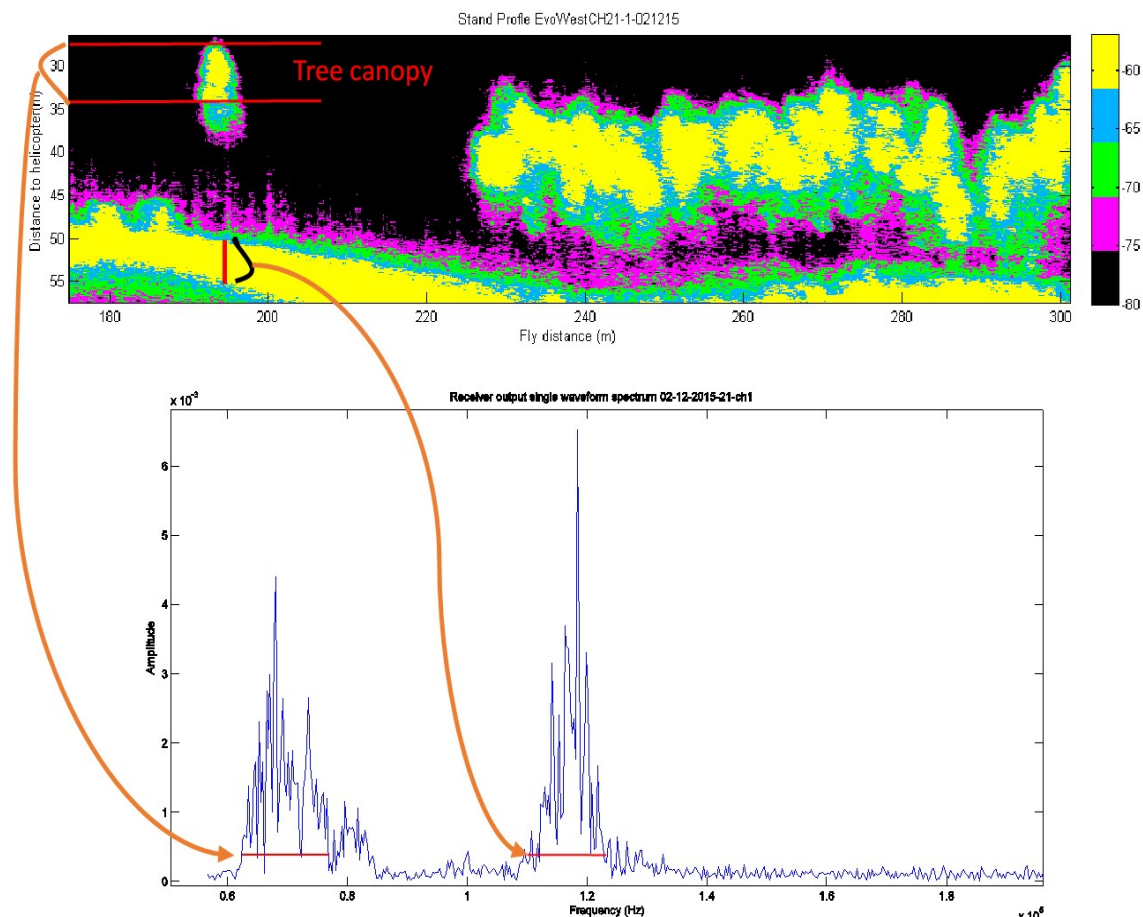


Figure 29: Relation between one stand profile (up) and frequency spectrum of one waveform (low)

in the diagram, there were two parts of frequencies with outstanding power levels which were 64 KHz to 76 KHz and 111 KHz to 122 KHz. After converting the frequencies into ranges and drawing it in the stand profile, this waveform is part of stand profile. The corresponding ranges for the mentioned frequencies were marked by the lines in Figure 29.

Consequently, the collected backscattered signals were all converted into frequency domain which were similar with the signal in the lower diagram in Figure 29 and then all the frequencies were converted into range and drawn together to generate a stand profile diagram. Furthermore, all the stand profile diagrams can be gathered to reconstruct the scanned forest. In following part, the information acquired from stand profile diagrams will be discussed.

6.3.1 System SNR Research

Signal Noise Ratio (SNR) is defined as the ratio of signal power and noise power [26]. SNR is a system key performance index which describes the comparison between desired signal level and noise level. As shown in section 4, TomoRadar has been

tested on the ground major for system calibration. However, during the calibration process, the system SNR was researched at the same time.

There are various factors composing the system noise. Generally the noise comes from two aspects, one is the system inherent noise including power noise, amplifier etc. , and the other is environment interference. To study the systematic noise level, the radar system has been held to radiate towards the sky where there was no any obstacle. The noise level in the incumbent system remains majorly around -95dB which is shown in Figure 30. The noise model was studied firstly.

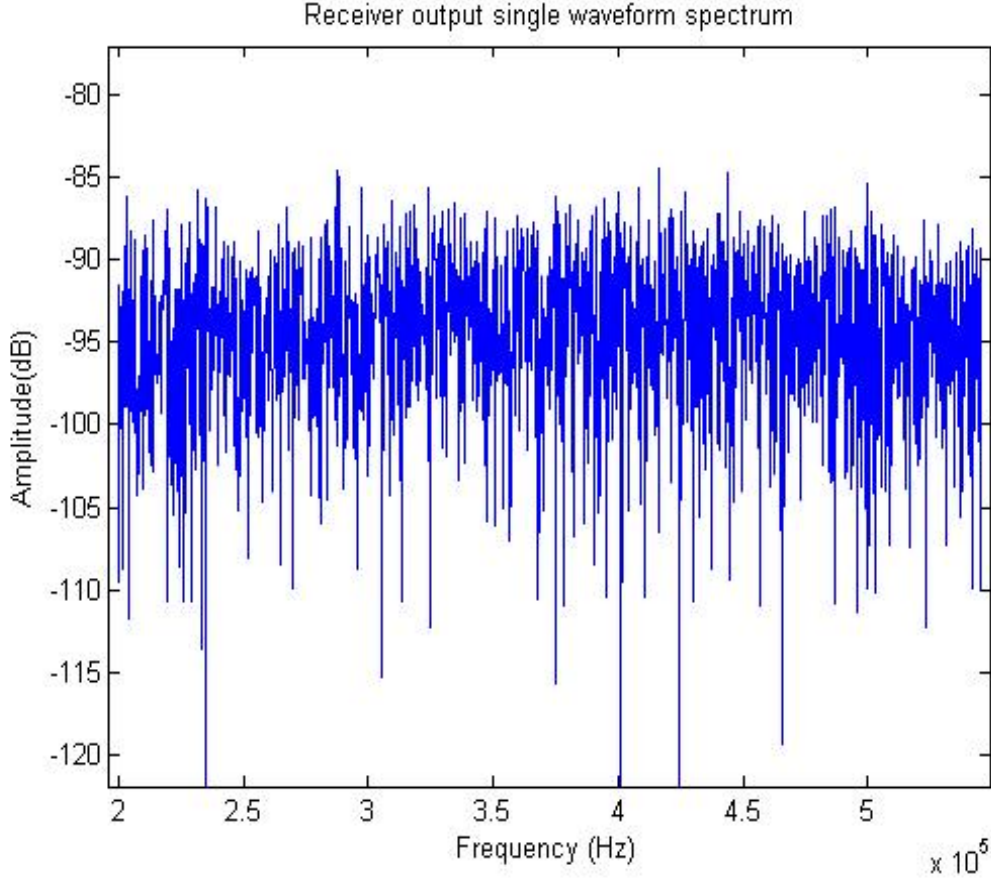


Figure 30: TomoRadar systematic noise

The distribution of noise was studied by Matlab signal processing tool, in which the noise amplitude distribution was simulated. The distribution fitting result is shown in Figure 31, and the result shows that the systematic noise obeys normal distribution. The normal distribution is a statistic distribution with Probability Density Function (PDF)

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}}e^{-(x - \mu)^2/(2\sigma^2)}, \quad (33)$$

In this distribution, μ is $8.85837e-05$ and σ is $3.96383e-05$. As the noise is normal distribution it is Gaussian noise.

The noise Power Spectral Density (PSD) was drawn as well which is shown in Figure 32. It can be seen that the noise has uniform power through the whole frequency band. Thus the noise is white noise. Consequently, when not considering multipath, forest clutter or other interferences the systematic noise is white Gaussian noise.

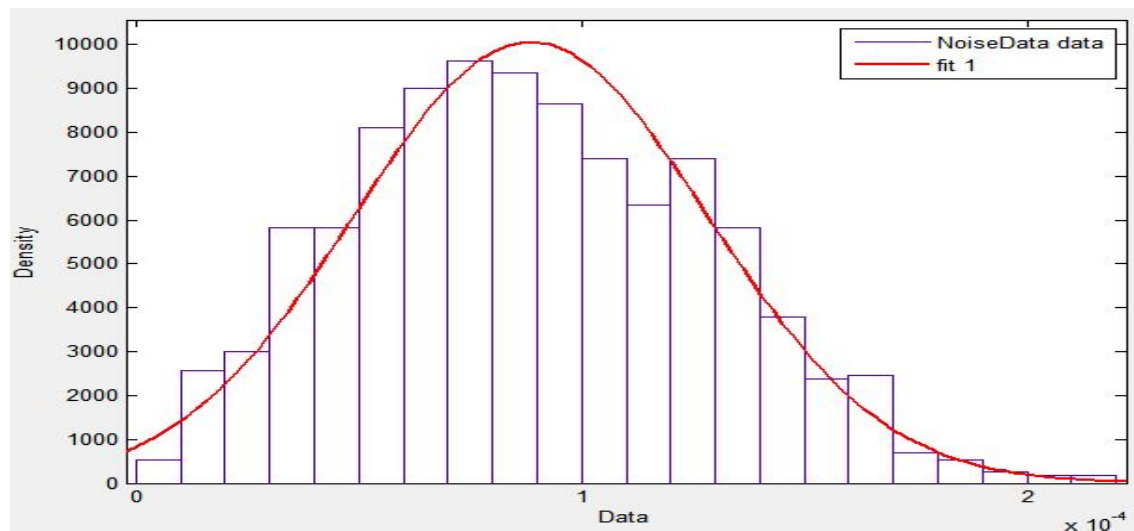


Figure 31: Noise data distribution

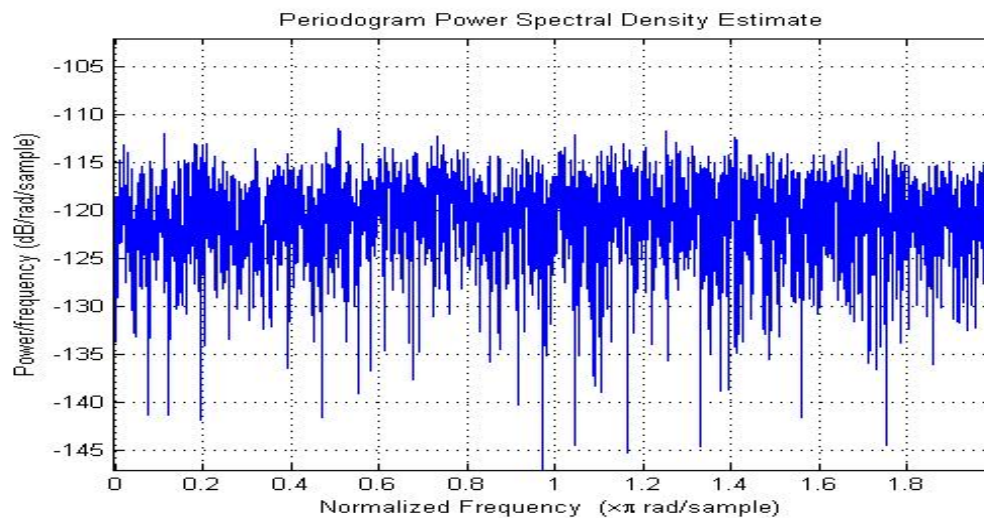


Figure 32: Noise power spectral density diagram

It can be seen that the noise level of TomoRadar is around -90 dB. When the system towards to ground, the backscatter signal from ground is shown in Figure 33. The amplitude of signal from Ground reaches at -30 dB. Therefore, the system signal noise ratio is 60 dB.

As said before, three different TomoRadar versions were tested in the flying tests. SNR was improved during the system upgrades. The first flying test was carried

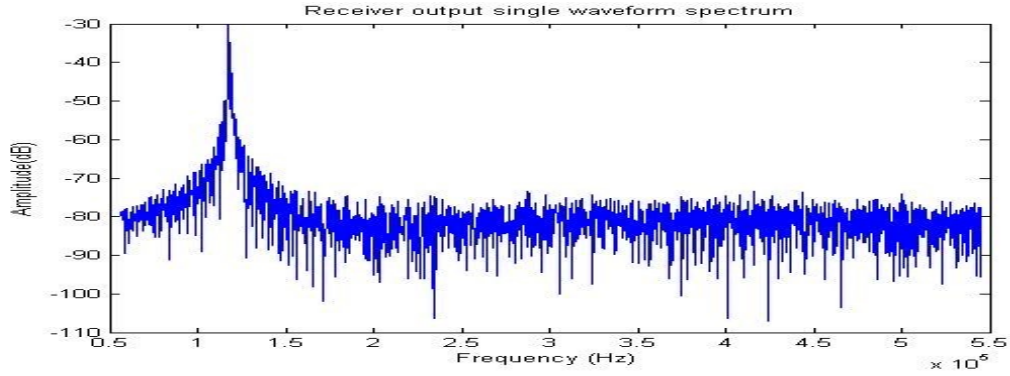


Figure 33: TomoRadar signal over ground

over FGI, while the other two were conducted over Evo. Therefore, the system SNR was analyzed and compared from the last two flying test results for they were generated from similar environment. All the backscattered signals were analyzed in frequency domain. The amplitudes of targets were recorded and compared. Two examples taken from the results were presented in following part. In Figure 34, the left diagrams presents the frequency spectrum of one waveform from 3rd version of TomoRadar, while the right one came from 2nd version system. It can be seen that in 2nd version, the noise floor was -70 dB, while the signal reached at -30 dB, and SNR was 40 dB. In 3rd version, the noise floor is around -85 dB which was similar with the result from field test. However, the maximum signal amplitude was -25 dB, and then SNR was 60dB. Consequently, the SNR of TomoRadar system improved after hardware upgrading.

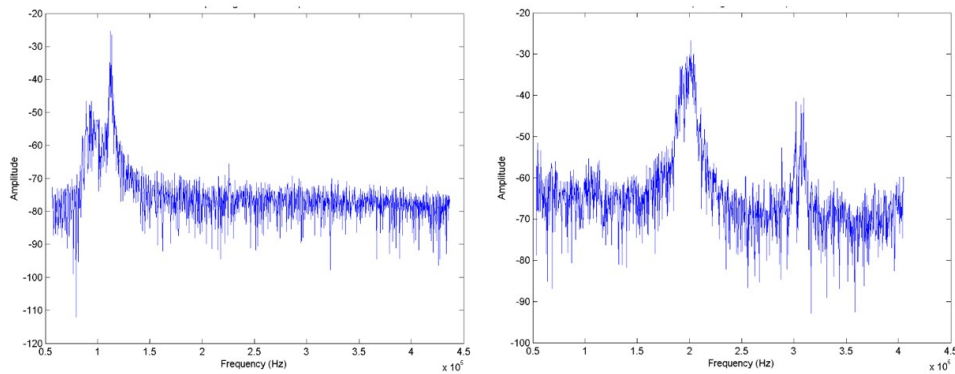


Figure 34: SNR comparison between two TomoRadar versions

When the system works, besides the targets backscattered signals there are usually some undesired echoes from other objects which locate around targets. These echoes are the so called clutter. Theoretically, the desired echoes should only come from the antenna main lobe which locates in 6 degrees beamwidth in TomoRadar. However, there are always clutters caused by side lobes, especially when the environment around target is complex.

As Figure 9 shows, the effects come from side lobe should be low enough. It was

designed that the clutters should not affect target echoes. From Figure 34 it can be seen that besides echoes from certain tree and corresponding ground, there is no other clutter affecting targets echoes. This result verifies that the radar design requirement is fulfilled and it can be concluded that the clutter has no significant effects on radar performance.

However, during the flying test, it was observed that the clutter might be big enough to be an interference when the tree leaves are wet enough. Therefore, the radar measurement results acquired from forest should be worse when leaves are too moisture theoretically.

6.3.2 System calibration verification

In chapter 5, the system calibration process was described. However, the calibration was carried on ground with range limitations. It was not known whether the calibration results was applicable when TomoRadar working in the air and scanning targets in 60 meters range. Figure 35 and Figure 36 were the stand profiles from same scanned data. The only difference was the data in one figure has been range calibrated, while the other one doesn't. The system calibration effects were studied through comparing both two analyzed results with ground truth data.

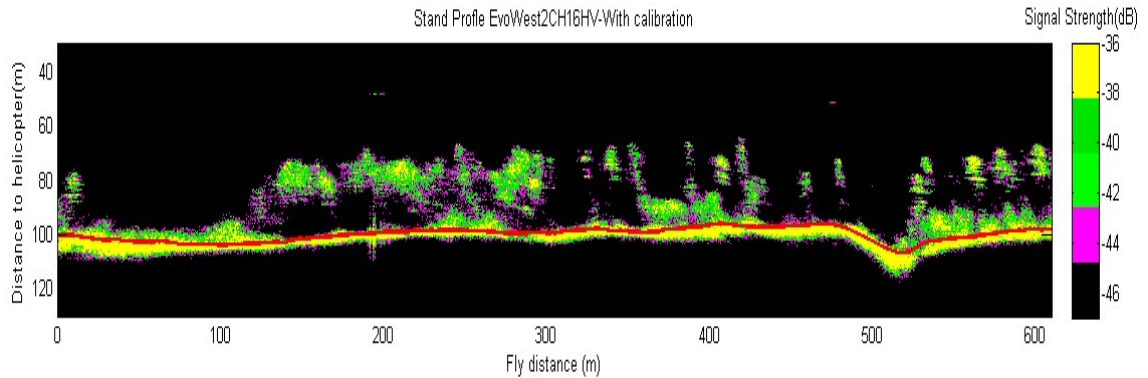


Figure 35: Stand profile with calibration and georeference data

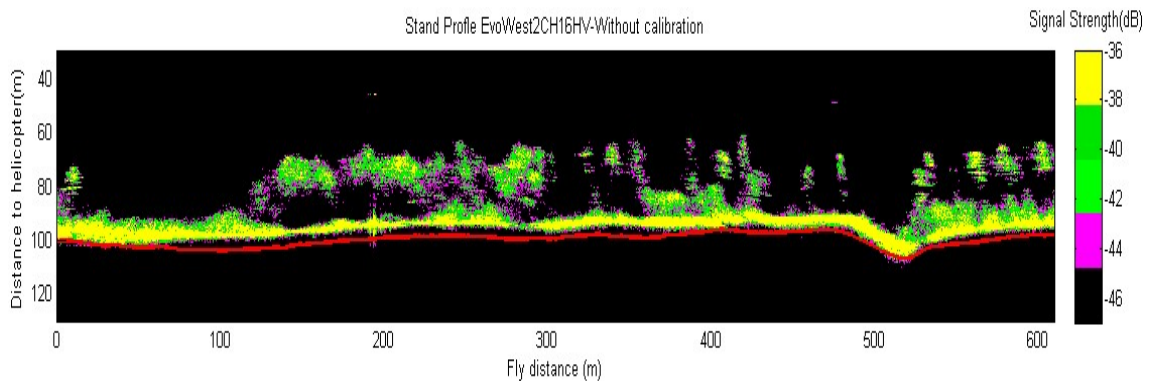


Figure 36: Stand profile without calibration and georeference data data

After the test, the recorded data has been processed as described in section 6.2. The range evaluated by equ.(26) was compared with the range derived by georeference data which was assumed to be the ground truth data. The result was shown in Figure 35. In addition, the evaluated range without calibration of same area was demonstrated in Figure 36.

In Figure 35, the red line was the fly height derived by georeference data, while other parts are the scanned area. The backscatter signal strength has been presented by different colors. Based on the range evaluated from intermediate frequency and the strength of frequency components, the forest shape can be drawn clearly. As the helicopter scanned over the Evo forest, the furthest probed place can be assumed to be ground and the distance to ground is fly height. From Figure 35, it can be seen that the ground evaluated by the range calibration result equation was overlapped with the ground derived by georeference data. When comparing with the range evaluation without calibration which is present in Figure 36, it was obviously that the range calibration help improve range evaluation accuracy. Thus the range calibration indeed help produce correct range evaluation from intermediate frequency.

What's more, it also verified that the range calibration conducted on ground in restrict distance works well in the long distance with more interferences. It is enough to conduct the range calibration of ranging radar system on ground in restrict distance.

Figure 35 proves that the range calibration result works which means that the relation between range and backscatter echo signal frequency is indeed linear. Through equ.(24), if the system sweep frequency is linear enough, the relation between range and IF of backscatter signal must be linear. Hence, the conclusion can be drawn that DDS installed in TomoRadar indeed produces linear enough sweep frequency waveforms.

6.3.3 Stand profile output analysis

As said before, the collected data would be converted into stand profiles to help figure out information on forest. In this section, more details around stand profiles were analyzed. The example stand profile diagrams were listed below.

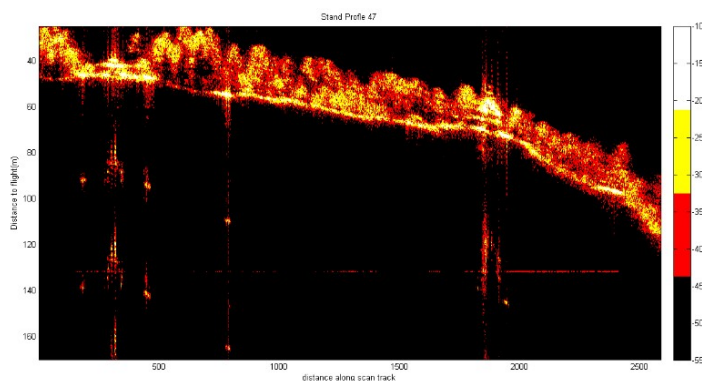


Figure 37: Example stand profile over FGI

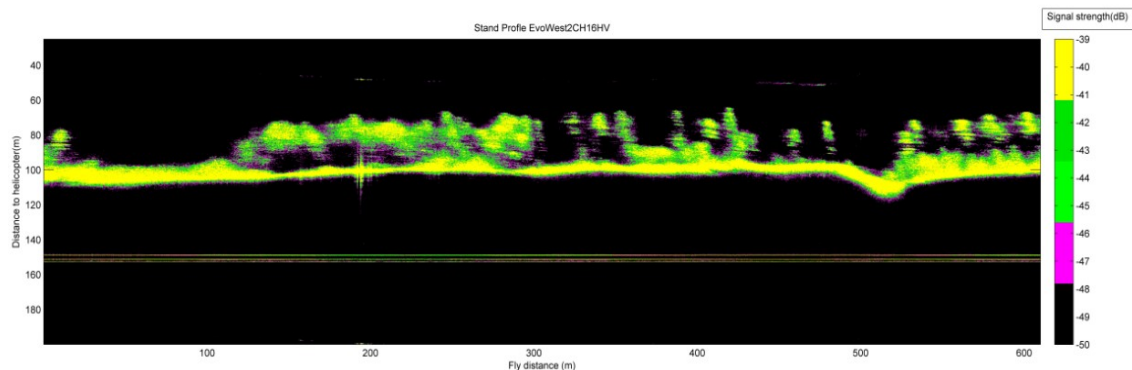


Figure 38: Example stand profile over Evo west v2

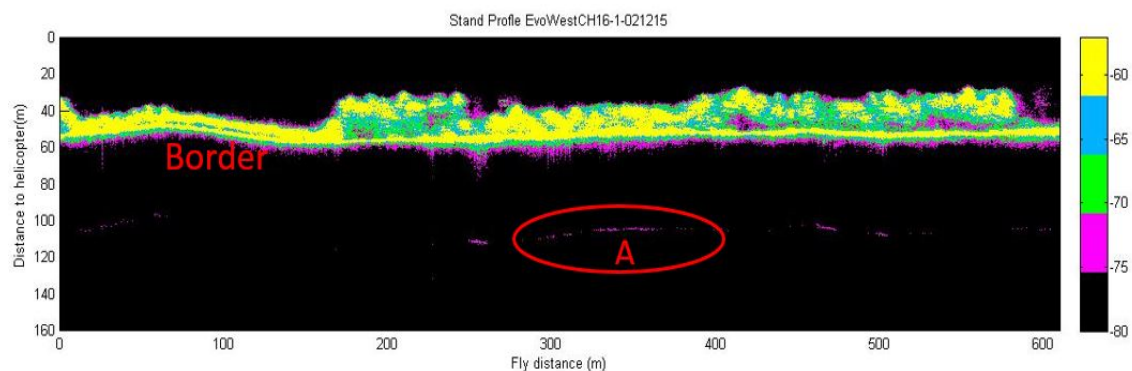


Figure 39: Example stand profile over Evo west v3

Figure 37, Figure 38, Figure 39 and Figure 40 were four stand profiles from three flying tests. In these stand profile diagrams, the tree shape can be recognized easily. In addition, the tree height can be estimated from the diagrams. These are the two most intuitive factors which can be observed from stand profile diagrams directly. What's more, the tree density was presented through the same color region.

In Figure 37, there are two parts having strong signal strength which even leads

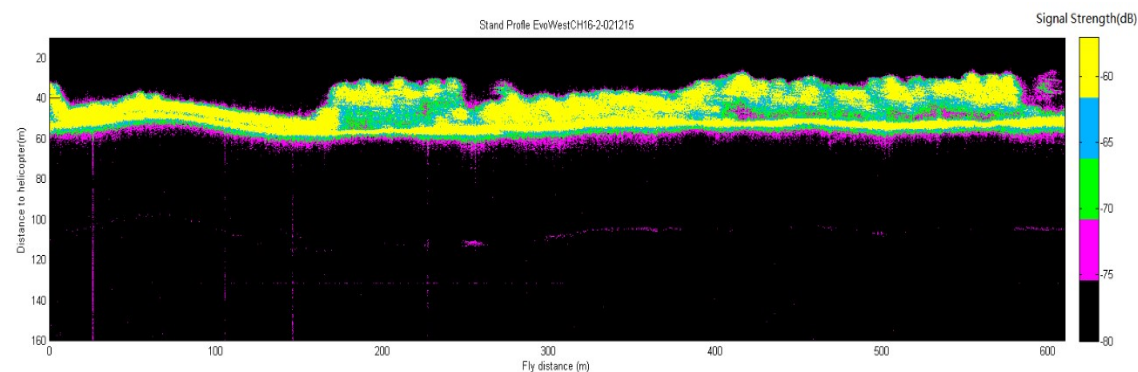


Figure 40: Example stand profile over Evo west v3 different channel

to signal saturation. The backscattered signal strength will be much bigger when coming from metal products, water (e.g. lake, sea), etc. rather than from trees. Considering the scanned location, surrounding and the target shape, the two targets which have bigger signal strength are assumed to be buildings or cars. Therefore, with TomoRadar not only trees can be investigated, but also the inside forest situation can be researched.

In Figure 38, besides continuous trees, there are some individuals can be viewed. It's clearly to judge that some of them were pines. This is the way to use TomoRadar stand profile diagrams to invest the tree species in forest. Similarly, the forest seasonal changes can be evaluated through TomoRadar data.

In Figure 39, there is a red line marked by circle A has similar shape with the targets image border. It can be seen that below the range of 5 meters, there is no echoes which proves that there is no reflected signals from helicopter body or rotor blade directly. As analyzed in chapter 5, there might be reflections caused by the helicopter rotating rotor blade from the ground. In this diagram, the red line is considered to be the reflection signal. Through the range scale it can be figured out that the frequencies of the signals which are presented by the red line is nearly two times of the targets frequencies. However, the amplitude of the reflected echoes is so small that never affect the target recognition. What's more, this reflected echoes have little effect on the target echoes intermediate frequencies. Thus, it can be seen that the M-D effect caused by helicopter rotating rotor blade was not critical and can be tolerated..

Figure 39 and Figure 40 came from same area in the same test. The backscattered signals from both these two stand profiles come from vertical transmit channel. The backscatter signal in Figure 39 was collected by vertical receiver channel, while the data in Figure 40 collected by horizontal receiver. It can be observed that the backscatter signal strength with vertical transmit channel and vertical receiver is stronger. Compare these two figures, the information presented on the diagrams is slightly different. This proves the benefit of collecting data from four different polarization models. However, there is no considerable difference between two different channels information, which is due to the 0 degree incident angle towards to the ground. In future work, the channel information diversity can be presented through applying distinct incident angles.

What's more, in both two figures, it can be assumed that there were at least two different kinds of plants. The taller parts marked with yellow color were assumed to be pine or spruce, while the shorter continuous parts were assumed to be bush.

In all four diagrams, there was a constant noise around 130 meters which was the so called power source noise. Such kind of noise was mostly caused by the ripples produced in the electrical components. This noise can be solved by redesigning the power circuit which is already done partly and will be upgraded in next TomoRadar generation as well. Comparing those four figures, this power noise was obviously in first two TomoRadar versions with the signal strength around -44 dB, while in the 3rd version, it was not obviously and the SNR was only -75 dB. Therefore the SNR was improved obviously as the TomoRadar upgrades.

What's more, the saturation phenomenon happened in Figure 31 appeared in

last two system versions flying tests as well. Whenever there were different targets including lake, building, and car etc., the strong backscattered signals from targets exceed expected value and lead to the signal saturation. To solve this problem, an amplifier called Automatic Gain Control (AGC) was under developing. With AGC, the amplifier gain will be different based on the backscattered signal strength. The backscattered signal with strong power will be amplified less to prevent the saturation.

At this moment, the collected TomoRadar data is pre-processed to simply generate the overview of probed area. Through the previous diagrams and analysis, TomoRadar data can be processed more accurately to present details. Moreover, the signal noise ratio is further improved according to the average filter even the SNR is sufficient with well hardware design. With these pre-processed data, further analysis around forest inventory, even bio information can be performed directly.

7 Conclusions

TomoRadar is designed as a ranging radar which is used to investigate forest. At this moment, the whole system platform has been constructed and it has been tested for three times based on helicopter. Through analyzing the collected data, the whole system is satisfied with the design requirements and the data is meaningful for forest study. The system contains four polarization modes, during the flying tests all the four channels perform well. The system range resolution study was performed. According to the test results, the conclusion can be drawn that for single target the minimum detect range is 0.15 meter. However, when there are more than one target and the targets have similar reflection coefficients, the minimum range between targets to guarantee that they can be recognized by radar system respectively depends on their distance to the system and their surrounding environment. There is no stable range value to assure the two targets recognition, and the theoretical range resolution 0.15 meter is difficult to be realized.

In addition, TomoRadar system range calibration and partly signal strength calibration were conducted. The range calibration was taken on the ground field in restrict range, but the result was verified to be able to apply on the radar working situation, that probing in long range. What's more, the range calibration process and results proved that the radar system frequency sweep is linear. In other word, the range calibration process proposed in this thesis work can help inspect the linearity of FM-CW radar system frequency sweep which is critical for the ranging radar system range resolution. In addition, partly radar signal strength calibration has been done based on the component properties. However, the power calibration result cannot be checked.

The system SNR was improved from around 35dB to 50dB. The collected data by TomoRadar was processed by Matlab and the output trees stand profile diagrams present lots of forest information, e.g. tree height, species, areas etc.. The high SNR assures high quality of stand profile diagrams. In the stand profile diagrams, besides expected trees targets signals, signal saturation happened occasionally. Combining the backscattered signal power strength and the test environment, the saturations were considered to be caused by the objects like lake, cars, building, etc..

In future work, the power calibration for the whole radar system will be carried based on the theories described in section 5.2. The system power source will be redesigned to decrease the noise caused by voltage ripples, in this way, the system SNR will be improved further. However, frequency window will be applied in signal processing process to help better SNR as well. For the saturation phenomenon, an amplifier named automatic gain control is under studying to reduce saturation.

As designed requirements, TomoRadar should also work based on UAV. At this moment TomoRadar has already been installed on UAV and has simple test, and the radar works properly. However, the system power source was found to be overheat and power consuming. When working on UAV, it is not possible to install enough battery packs with the radar system as working on helicopter. Therefore, one more requirement for the new designed power source is less heat producing. While, the calibration and signal processing for UAV based TomoRadar will be researched

afterwards as well.

References

- [1] R. Bernard, M.E. Frezal, D.Vidal-madjar, D.Guyon and J.Riom. Nadir looking airborne and possible applications to forestry. *Remote Sensing of Environment*,1987,vol. 21, pp. 297–309.
- [2] L. Prevot, I. Champion, G. Guyot. Estimating surface soil moisture and leaf area index of a wheat canopy using a dual-frequency (C and X bands) scatterometer. *Remote Sensing of Environment*,1993,vol. 46, pp. 331–339.
- [3] Moran, M.S. Vidal, A. Troufleau, D. Inoue, Y. Mitchell, T.A., Ku- and C-band SAR for discriminating agricultural crop and soil conditions, *IEEE Geoscience and Remote Sensing Society*,1998,vol. 36, pp. 265–272.
- [4] Y. Inoue, T. Kurosu, H. Maeno, S. Uratsuka, T. Kozu, K.Dabrowska-Zielinska, J.Qi, Season-long daily measurements of multifrequency (Ka, Ku, X, C, and L) and full-polarization backscatter signatures over paddy rice field and their relationship with biological variables, *Remote Sensing of Environment*,2002, vol. 81,pp. 194—204.
- [5] T. Le Toan, A. Beaudoin, J. Riom, and D. Guyon, Relating Forest Biomass to SAR Data, *IEEE Transactions on Geoscience and Remote Sensing*,1992, vol. 30, NO. 2
- [6] Svein Solberg, Rasmus Astrup, Terje Gobakken, Erik Næsset and Dan J. Weydahl, Estimating spruce and pine biomass with interferometric X-band SAR, *Remote Sensing of Environment*, 2010, vol. 114, pp. 2353—2360.
- [7] Hallikainen, M., Hyypä, J., Haapanen, J., Tares, T., Ahola, P., Pulliainen, J. and Toikka, M., A helicopter-borne 8-channel ranging scatterometer for remote sensing,part 1: System description, *IEEE Transaction on Geoscience and Remote Sensing*, 1993, vol. 31, No. 1, pp. 161–169.
- [8] Juha Hyypä, Martti Hallikainen, A helicopter-borne 8-channel ranging scatterometer for remote sensing,part II: Forest Inventory, *IEEE Transaction on International Geoscience and Remote Sensing*, 1993, vol. 31,No. 1,pp. 170–179
- [9] Juha Hyypä and Martti HaUikainen, Applicability of Airborne Profiling Radar to Forestry Inventory, *Remote Sensing of Environment*, 1996, vol. 57, pp. 39–57.
- [10] Praks, J., Kugler, F., Papathanassiou, K.P.,Hajnsek, I., Hallikainen, M., Height Estimation of Boreal Forest: Interferometric Model-Based Inversion at L- and X-Band Versus HUTSCAT profiling Scatterometer, *IEEE Geoscience and Remote Sensing Letters*,2007, vol. 4, No. 3,
- [11] Juha Hyypä. Development and Feasibility of Airborne Ranging Radar for forest Assessment. Doctor thesis, Helsinki University of Technology, Espoo, Finland, 1993.

- [12] Markus Pichler, Andreas Stelzer, Peter Gulden, and Martin Vossiek, Influence of Systematic Frequency-Sweep Non-Linearity on Object Distance Estimation in FMCW/FSCW Radar Systems, *Microwave Conference 33rd European*, 2003, Vol. 3, pp. 1203–1206.
- [13] S. Scheiblhofer, S. Schuster, and A. Stelzer, High-speed FMCW radar frequency synthesizer with DDS based linearization, *IEEE Microwave and Wireless Components Letters*, 2007, vol. 17, No. 5, pp. 397–399.
- [14] Merrill I. Skolnik, *Radar handbook*, 3. Edition, McGraw-Hill Education, 2008
- [15] Instrument Description: Spaceborne Scatterometers. Created 01.2005. Updated 08.2008. https://nsidc.org/data/docs/daac/scatterometer_instrument_gd.html
- [16] S. H. Yueh, R. Kwok, Shu Hsiang Lou, Wu Yang Tsai, Sea ice identification using dual-polarized Ku-band scatterometer data, *IEEE Transactions on Geoscience and Remote Sensing*, 1997, vol. 35, pp. 560—569.
- [17] J. Figa, A. Stoffelen, On the assimilation of Ku-band scatterometer winds for weather analysis and forecasting, *IEEE Transactions on Geoscience and Remote Sensing*, 2000, vol. 38, pp. 1893–1902.
- [18] Ghada M. SAMI, Radio Wave Propagation Characteristics in FMCW Radar, *Electromagnetic Analysis & Applications*, 2009, vol. 1, pp. 275–278.
- [19] Graham Brooker, High Range-Resolution Techniques, *Introduction to Sensors for Ranging and Imaging*, SciTech Publishing, 2009, pp. 303–356.
- [20] Eva Murphy, Colm Slattery, All About Direct Digital Synthesis, *Analog Dialogue* 38-08, 08, 2004.
- [21] Jouko Vankka, Direct Digital Synthesizers: Theory, Design and Application, Ph.D. dissertation, Helsinki University of Technology, Helsinki, Nov, 2000.
- [22] G. Brooker, Understanding millimeter wave FMCW radars, *1st International Conference on Sensing Technology*, 2005, pp. 153–157.
- [23] Hyypä, J, Makynen, M, Hallikrainen, M.T., Calibration accuracy of the HUTSCAT airborne scatterometer, *IEEE Transactions on Geoscience and Remote Sensing*, 1999, vol. 37, pp. 1450—1454.
- [24] Henk J. Buiten, Jan G.P.W. Clevers, *Land Observation by Remote sensing*, chapter 8, Technology & Engineering, 1994.
- [25] Victor C. Chen, Hao Ling, “Time-Frequency Transforms for Radar Imaging and Signal Analysis”, chapter 8, 1st Edition, 2002
- [26] Carlson B. Communication Systems: an Introduction to Signals and Noise in Electrical Communication. New York: McGraw-Hill, pp. 495, 1968

A Four channels TomoRadar signal processing with Matlab

```
%%%%% TomoRadar test data processing %%%%%%%%%%%
clear all;
files= dir('*.*bin');
%% Check all the binary files in the folder

files_index=dir('*.*txt');
%% Check all the text files (channel switching log)

NumberOfFile=size(files,1);
%% Total number of processed files

%% For loop, call data processing function to process
%% all the files in same folder one by one
for i=1:NumberOfFile
p=ceil(i/2);
s=files(i).name;
index=files_index(p).name;

if(files(i).isdir==0)
ImportdataFFTandPlot(s,index,p,i);
%% Call data processing function
end
end
```

B One receiver channel data process function

```

function [h1,h2]=ImportdataFFTandPlot(s,index,p,i)
%%% h1: One transmit channel backscatter signal stand profile plot handle
%%% h2: another transmit channel backscatter signal stand profile plot handle
%%% s: string type. The processed file's name
%%% index: string type. The transmitter polarization switching log
%%% p: number of the switching log
%%% i: number of the processed files
%%% this function is used to process one receiver
%%% channel file and save the result into a figure;

%%% Open the data file with the file name %%%%%%%%%%%
fileID = fopen(s);
A = fread(fileID,[7500,inf], '*single', 0, 'b'); % big ending in binary file
fclose(fileID);

%%% Open the transmitter channel switching log files %%%%%%%%%%
%%% Divide the two transmission channel data from one receiver channel file
CHindex=importdata(index);
CHindex=vertcat(1,CHindex);
CH1index= find(CHindex); %% positive voltage
CH2index= find(CHindex==0); %% 0 voltage
y1= A(:,CH1index); %% positive transmission channel
y2= A(:,CH2index); %% 0 voltage level transmission channel

%%%%%%%% Parameters setting before data processing FFT %%%%%%%%%%%
fs=2.5e6; % Sampling frequency is 2.5MHz;
L=7500; % Length of one waveform data;
NFFT = 2^nextpow2(L); % Next power of 2 from length of A
m1=size(y1,2); % find number of signal matrix columns
m2=size(y2,2); % find number of signal matrix columns
D1=25;
D2=200; % Stand profile display range
v=10; % Estimate helicopter flying speed

%%% FFT transform preparation %%%%%%%%%%
fReso= fs/NFFT;
Nmin= round((2170,7*D1 +2589,3) /fReso);
Nmax = round((2170,7*D2 +2589,3) /fReso);
f =(Nmin:Nmax)*(fs/NFFT); %% spectrum x axis,

%%%%%%%%%% Low sample to reduce data amount %%%%%%%%%%
yresample1=y1;
length1=size(yresample1,2);

```

```

yresample2=y2;
length2=size(yresample2,2);

%% FFT by function %%%%%%%%%%%
yresample1=double(yresample1);
FA1=fft(yresample1,NFFT,1)/L;
yresample2=double(yresample1);
FA2=fft(yresample2,NFFT,1)/L;

%% Transmitter channel 1 data processing %%%%%%%%%%
%% Power calibration offset calculation %%%%%%%%%%
f2 =(0:NFFT-1)*(fs/NFFT); %% for the whole file
offset2= 0.0124*(f2/1000) - 0.8276;
offset2=offset2';
offsetr=repmat(offset2,1,length1);

%% convert signal in frequency into
%% decibel mode and add power calibration
Sigaftercal=20*log10(abs(FA1))+offsetr;
%% average value every ten columns %%%%%%%%%%
k=5;
y=Sigaftercal;
while k<(length-4)
x= Sigaftercal(:,(k-4:k+5));
y(:,k)=mean(x,2);
k=k+1;
end
%%%%%%%%%% stand profile plot %%%%%%%%%%
yaxis=fliplr((f(:)-2589,3)*(1/2170,7));
%% Stand profile y axis calculation
xaxis=(v/fm)*(1:length);
%% x axis calculation by flying distance
c=rem(i,2);
map = [0, 0, 0
1, 0, 0
1, 1, 0
1, 1, 1];

h1=imagesc(xaxis,yaxis,y(Nmin:Nmax));
%% Plot stand profile
colormap (map);
caxis([-47, -36])
colorbar;
xlabel('distance along scan track');
ylabel('Distance to flight(m)');

```

```

title(sprintf('Stand Profile %d-TansChan1-RecChan %d',p,c));
whitebg('white'); %% change background color
saveas(h1,sprintf('Test File %d_TansChan1_RecChan %d',p,c),'png');
%% save the diagram

%%% Transmitter channel 2 data processing %%%%%%%%%%
%%% Power calibration offset calculation %%%%%%%%%%
f2 =(0:NFFT-1)*(fs/NFFT); %% for the whole file
offset2= 0.0124*(f2/1000) - 0.8276;
offset2=offset2';
offsetr=repmat(offset2,1,length2);

%% convert signal in frequency into decibel
%% mode and add power calibration
Sigaftercal=20*log10(abs(FA2))+offsetr;
%%% average value every ten columns %%%%%%%%%%
k=5;
y=Sigaftercal;
while k<(length-4)
x= Sigaftercal(:,(k-4:k+5));
y(:,k)=mean(x,2);
k=k+1;
end
%%%%%%%%%% stand profile plot %%%%%%%%%%
h2=imagesc(xaxis,yaxis,y(Nmin:Nmax));
%% Plot stand profile
colormap (map);
caxis([-47, -36])
colorbar;
xlabel('distance along scan track');
ylabel('Distance to flight(m)');
title(sprintf('Stand Profile %d-TansChan0-RecChan %d',p,c));
whitebg('white'); %% change background color
saveas(h2,sprintf('Test File %d_TansChan0_RecChan %d',p,c),'png');
%% save the diagram

end

```

C Single wave form in frequency in frequency domain

```

fileID = fopen('20151202_122758_Tomo00021.tdmsCH1.bin');
%% Import binary file
Tem = fread(fileID,[7500,3145],'*single', 0, 'b');
%% big ending in binary file
A= fread(fileID,[7500,1],'*single', 0, 'b'); %% getting the 3146th wave form
fclose(fileID);

%%% Parameters setting %%%%%%%%%%%
fs=2.5e6;          % Sampling frequency is 2.5MHz;
fm=163;           % Modulation Frequency 163Hz.
L=7500;           % Length of data;
NFFT = 2^nextpow2(L); % Next power of 2 from length of A
D1=25;
D2=200;          % Stand profile display distance
v= 10;           % Helicopter fly speed 10 m/s

%%% FFT transform of received signal
%%% and spectrum diagram %%%%%%%%%
fReso= fs/NFFT;   % frequency resolution

Nmin= round((2170.7*D1 +2589.3) /fReso);
Nmax = round((2170.7*D2 +2589.3) /fReso);
%% find the number of data that reaches the frequency of distance D
f =(Nmin:Nmax)*(fs/NFFT);
%% spectrum x axis, cut first big noise and high frequency noise
yresample=A;
length=size(yresample,2);
%%% Plot received signal in frequency domain %%%%%%%%%%%
yresample=double(yresample);
FA=fft(yresample,NFFT,1)/L;
%% converting signal into frequency domain

figure(1)
% plot(f,20*log10(abs(FA(Nmin:Nmax))));
%% Spectrum diagram in dB
plot(f,abs(FA(Nmin:Nmax))); %% Spectrum diagram in linear case
title('Receiver output single waveform spectrum ');
xlabel('Frequency (Hz)')
ylabel('Amplitude')

```