

Development of Software-Defined Multichannel Receiver for Equatorial Atmosphere Radar (EAR)

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Abstract

Equatorial Atmosphere Radar (EAR) is a very high frequency (VHF) Doppler radar operated with an active phased-array antenna system at 47 MHz. It had originally been equipped with a single receiving channel system since its establishment in 2001 at the equator in Kototabang, West Sumatra, Indonesia (0.20°S , 100.32°E). This research presents development of a multichannel receiver system for the EAR using a combination of the Universal Software Radio Peripheral X300 (USRP X300) and GNU Radio software. There are a number of advantages to have multichannel receiver system such as to enable spaced-antenna method and spatial domain interferometry.

First test observation was conducted on November 2017 to analyze the system reliability, followed with subsequent tests in March and July 2018. Two USRP X300 devices, corresponding to four receiving channels, were synchronized using 10 MHz reference clocks and a pulse per second (1 PPS) signal. The standard observation system of the EAR is retained by splitting the received echo signals through directional coupler which enabled simultaneous observation of the two different techniques, spaced-antenna and Doppler beam swinging. The signal for spaced-antenna application is fed to the USRP X300s for digital conversion, and then stored on a Hard Disk Drive (HDD). The ranging of the data is carried out by taking advantage of the leaked transmitted pulse, before demodulated and coherently integrated.

Further, performance analysis using multiple receiving antennas orientation for the application of spaced-antenna method on the EAR has been carried out through multiple experiments over the duration between April 2019 and September 2019. Phase correction is applied to all channels for a single spectrum in the real time signal processing for improving the phase synchronization. The initial results show the existence of noticeable fluctuations in the estimated horizontal wind. Then, a comparison of the EAR

spaced-antenna (SA) performance with five different orientations taking into consideration the size of receiving antenna and its separation distance has been presented, where the horizontal wind profiles using Full Correlation Analysis (FCA) were estimated and compared with the standard EAR data. Based on the results, the configuration with the largest aperture shows slight advantage over the other four configurations but with limited improvement.

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Abbreviations

ADC	A nalog to D igital C onverter
ANT	A ntenna A rray
BLR	B oundary L ayer R adar
CPEA	C oupling P rocesses in the E quatorial A tmosphere
CPL-IN	C oupled- I nput
CPL-OUT	C oupled- O utput
DBS	D oppler B eam S winging
DC	D irect C urrent (0 Hz)
EAR	E quatorial A tmosphere R adar
EEPROM	E lectrically E rasable P rogrammable R ead- O nly M emory
FCA	F ull C orrelation A nalysis
FDI	F requency D omain I nterferometry
FFT	F ast F ourier T ransform
FPGA	F ield P rogrammable G ate A rray
GB	G igabyte
GigE	G igabit E thernet
GPP	G eneral P urpose P rocessor
GRC	G NU R adio C ompanion
HC	H ost C omputer
HDD	H ard D isk D rive
IF	I ntermediate F requency
IPP	I nter P ulse P eriod
IQ	I n-phase and Q uadrature-phase
MIMO	M ultiple I nput M ultiple O utput
PC	P ersonal C omputer

PPS	P ulse P er S econd
RASS	R adio A coustic S ounding S ystem
RF	R adio F requency
RIM	R ange I maging
SA	S paced- A ntenna
SDI	S patial D omain I nterferometry
SDM	S oftware- D efined M ultichannel Receiver
SDR	S oftware- D efined R adio
SFP+	Enhanced S mall F orm-factor P luggable
SMD	S ignal M odulator and D emodulator
SNR	S ignal-to- N oise R atio
SP	S ignal P rocessor
SWIG	S implified W rapper and I nterface G enerator
TRX	T ransmitter and R eceiver Module
TTL	T ropical T ropopause L ayer
UHD	U SRP H ardware D river
USRP	U niversal S oftware R adio P eripheral
VHF	V ery H igh F requency

Chapter 1

General Introduction

1.1 Overview of RADAR

Radio Detection And Ranging or radar is a general remote sensing technique that uses a variety of radio frequencies for detecting specific targets. The radio frequency is typically designated to a specific bands based on its applications as summarized in Table 1.1.

TABLE 1.1: Designations of radio frequency bands [1]

Name	Frequency	Wavelength
Low frequency (LF)	30 - 300 kHz	10 - 1 km
Medium frequency (MF)	0.3 - 3 MHz	1000 - 100 m
High frequency (HF)	3 - 30 MHz	100 - 10 m
Very high frequency (VHF)	30 - 300 MHz	10 - 1 m
Ultra high frequency (UHF)	300 - 3000 MHz	1 m - 10 cm
Microwave region	≥ 3000 MHz	≤ 10 cm
<i>Further – subdivision</i>		
L-band	1 - 2 GHz	30 - 15 cm
S-band	2 - 4 GHz	15 - 7.5 cm
C-band	4 - 8 GHz	7.5 - 3.75 cm
X-band	9 - 12 GHz	3.75 - 2.5 cm
K-I (or K_u) band	12 - 18 GHz	2.5 - 1.7 cm
K-II (or K_a) band	27 - 40 GHz	1.2 - 0.75 cm

Radar is used in many applications such as military, weather forecasting, astronomy, ocean surveillance and flight control system to name a few where each application incorporates different frequency, radar type, and signals processing technique. The type of radars are distinguishable through its operating principle, frequency and few other factors. For example, atmospheric radar could also be referred as weather radar, MST radar, and wind profiler due to their observation area which is located within atmosphere.

However, in this thesis, atmospheric radar will be specifically defined as a radar that measure clear air atmosphere (i.e., ST/MST radar and wind profiler). M, S and T stands for Mesosphere, Stratosphere and Troposphere, respectively, which describes the layer of atmosphere to be observed. Weather radar however is not considered atmospheric radar in this regard because the intended scatterer is hard scatterer and typically referred as meteorological radar. Regardless of the type of radar, a similar concept is used where electromagnetic wave is radiated through the antenna into space, then a portion of its echo which being scattered by radar target is received, converted into baseband and further processed for their intended purposes. However, a different principle of operation is perceivable depending on the type of radar target.

Radar is able to measures target's location and its movement. The time taken for the echo of the radiated electromagnetic wave to return to the radar receiver is used to estimate the range of the target, r which could be expressed in a general term as follows:

$$r = \frac{c\tau}{2} \quad (1.1)$$

where $c = 3 \times 10^8 \text{ms}^{-1}$ is the speed of light and τ is the time delay of an echo.

1.1.1 Radar equation

Radar equation is one of the important aspects when designing radar system. It shows a relation between the transmitted and received power after considering other parameters such as the antenna gain, range and the scattering cross section of the targets. In general, radar equations are distinguishable between hard scatterer and soft scatterer,

single target and distributed target. For a single target, it is expressed in a general term as:

$$P_r = \frac{P_t A_e^2 L}{4\pi \lambda^2 r^4} \sigma \quad (1.2)$$

where P_r and P_t are received and transmitted power, respectively, A_e is the effective area of the antenna, L is the loss factor, λ is the radar wavelength, r and σ are the range and the cross section of the target respectively.

It is clear from the equation (1.2) that the received echo power is inversely proportional to the range, r by power of four. However for a distributed targets which defined by a scattering volume, V , the proportionality is to the inverse of range square, r^2 as expressed in the following expression:

$$P_r = \frac{P_t A_e \pi a^2 \Delta r L}{64 r^2} \eta \quad (1.3)$$

where a is a non-dimensional factor which concerns the non-uniformity of illumination of the antenna and Δr is the size of the range cell. The numerators of the equation (1.3) are directly influenced by the spatial resolution of the radar, antenna diameter (i.e., circular antenna) and the range cell size. Volume reflectivity, η increases linearly as volume increases, assuming uniform distribution of the scatterer in a unit volume and expressed as:

$$\eta \equiv \frac{d\sigma}{dV} \quad (1.4)$$

1.1.2 Radio refractive index

Echoes from atmospheric radar observation are scattered due to the fluctuation of radio refractive index, n . This mechanism is also called as Bragg scattering. In mathematical expression, n is defined as [2]:

$$n - 1 = \frac{3.75 \times 10^{-1} e}{T^2} + \frac{7.76 \times 10^{-5} P}{T} - \frac{N_e}{2N_c} \quad (1.5)$$

where e (hPa) is the partial pressure of water vapor, P (hPa) is the total atmospheric pressure, T (K) is the absolute temperature, N_e and N_c is the number of electrons and the critical plasma density, respectively. Based on equation (1.5), the variation in n is contributed differently by different characteristics of atmosphere layer as depicted in Figure 1.1 (right). The influence of water vapor and dry air are significant for observation below 40 km of the atmosphere while in the upper atmosphere, free electron is the main contributor to the fluctuation of n . In the lower and middle atmosphere (i.e., 100 km and below) atmospheric turbulence is known as the major source of radiowave scattering. This component is called coherent scattering because the fluctuation of n is caused by a large number of molecules and/or electrons which contribute to the scattered electric field coherently in phase.

1.1.3 Partial reflection

Partial (or Fresnel) reflection is induced by a horizontal layer which extends over wide area. It occurs from a well stratified atmosphere which acts like a mirror. The mechanism from partial reflection is different than scattering from refractive index perturbation where a small reflection coefficient, ρ is considered when deriving radar equation which is expressed as:

$$P_r = \frac{P_t A_e^2 L}{4\lambda^2 r^2} |\rho|^2 \quad (1.6)$$

where ρ has a complex value of $|\rho|^2 \leq 1$. Equation (1.6) becomes analogous to a one-way transmission from an antenna to its mirror image located at range $2r$. Echo from partial reflection is generally stronger when the antenna beam is perpendicular to the layer, but will significantly falls off as the angle is slanted.

1.1.4 Principles of Doppler method

One of the main purposes of atmospheric radar is to determine the motions of scatterers and wind patterns. It could be measured by applying the Doppler effect which was first proposed by C.J. Doppler in 1842. In a typical radar, echoes from a moving target will produce frequency shift (or Doppler shift, f_d) which could be expressed as:

$$f_d = -\frac{2f}{c}v_d \quad (1.7)$$

where v_d is the Doppler velocity of the target. If the scatterer moves toward the radar, positive Doppler shift is obtained, and the Doppler velocity (or radial velocity of the scatterer) is negative. The Doppler shift is negative if the scatterer moves away from the radar, where the Doppler velocity is positive. To determine the shifted frequency based on the received echo, the carrier frequency of the radiowave will typically be shifted to a baseband (0 Hz). However, for atmospheric radar, where short pulse is used, measurement of Doppler shift is practically carried out using the change of the echo's phase angle within one transmitted pulse to the next. The phase angle, φ is expressed as:

$$\varphi = -\frac{4\pi r}{\lambda} + \varphi_0 \quad (1.8)$$

where r is the range to the scatterer, λ is the radar wavelength, and φ_0 is the initial phase of the transmitted signal. The rate of phase change can be expressed as:

$$\frac{d\varphi}{dt} = -\frac{4\pi}{\lambda} \frac{dr}{dt} \quad (1.9)$$

1.1.5 Pulse compression

If we consider the expression from equation (1.3), radar return power could be increased by transmitting higher transmitted power or by using longer pulse. However, if longer pulse is used then the range resolution will be degraded. To mitigate the issue, pulse compression is introduced where a longer pulse will be coded with specific sequence, and the return signal will be demodulated and decoded where the sequence is known to the receiver. Through such technique, the signal to noise ratio (SNR) can be improved while retaining a good range resolution of the radar. Pulse compression techniques for radar application is divided into linear Frequency Modulation (FM) chirping and phase coding, where phase coding technique is further divided into a few different methods such as Barker codes, complementary codes and Pseudo-Barker code.

One of the important breakthrough in the generation and implementation of complementary codes is the use of truncated codes by Spano and Ghebrehbrhan [3]. The technique uses a set of $N/2$ complementary code pairs for code length of N ($N = 4, 8, 16, 32$, etc.) to obtain a diagonal decoding matrix M that enables the full decoding of truncated ranges without the need of matrix inversion, and resulting in optimum performance with regards to the signal to noise ratio degradation (SNRD) in the truncated ranges. By arranging the order of transmission of the code sequences systematically to increase the suppression of sidelobes resulting from atmospheric characteristics, and by performing appropriate steps to reduce the effects of interferences, it simultaneously optimizes the performances with regards to SNRD, sidelobe suppression, and interference rejection. The use of Spano complementary codes allow for boundary layer measurement at lower altitudes than were previously possible.

1.2 Research Background

Study of the Earth's atmosphere has become one of a major concerns among researchers and meteorologists due to its importance towards understanding global energy circulation and redistribution around the Earth. Atmospheric region is characterized based on its altitude where below 10 km is regarded as lower atmosphere while middle atmosphere is generally considered between 10 km to 100 km [1]. It is commonly classified based on the structure of temperature vertical profile and electron density. Figure 1.1 (left) shows the temperature profile of atmosphere from U.S. standard atmosphere 1976. The lowest region is troposphere with constant temperature decrease of about 6.5 K km^{-1} , viewed from surface to higher altitude of about 10 km. Next, stratosphere is the region where temperature is increasing with increasing height due to heat absorption by the ozone layer between about 12 km and 48 km. The upper layer is mesosphere with decreasing temperature profile of up to about 85 km because there is no ozone-like mechanism to trap heat. Then, thermosphere from 90 km up to more than 100 km has an increasing temperature profile over height because this layer is directly hit by the solar radiation.

The boundary between two atmosphere layers are called tropopause (between troposphere and stratosphere), stratopause (between stratosphere and mesosphere) and mesopause (between mesosphere and thermosphere). Tropopause is a thin layer where mixing and heat transport by convection occurs. In the tropics, tropopause is often called as

tropical tropopause layer (TTL) and typically associated with Kelvin waves. TTL is important in atmospheric study as it acts as a gate to the stratosphere for atmospheric tracers such as water vapor and so-called very short lived (VSL) substances, which both play an important role for stratospheric chemistry [4]. Phenomenon that are occurring in this layer will directly affect the weather of the Earth, thus study of this layer attracts interest from many researcher such as Mega et al. [5], Taylor et al. [6], Fujiwara et al. [7] and Ortland and Alexander [8], to name a few.

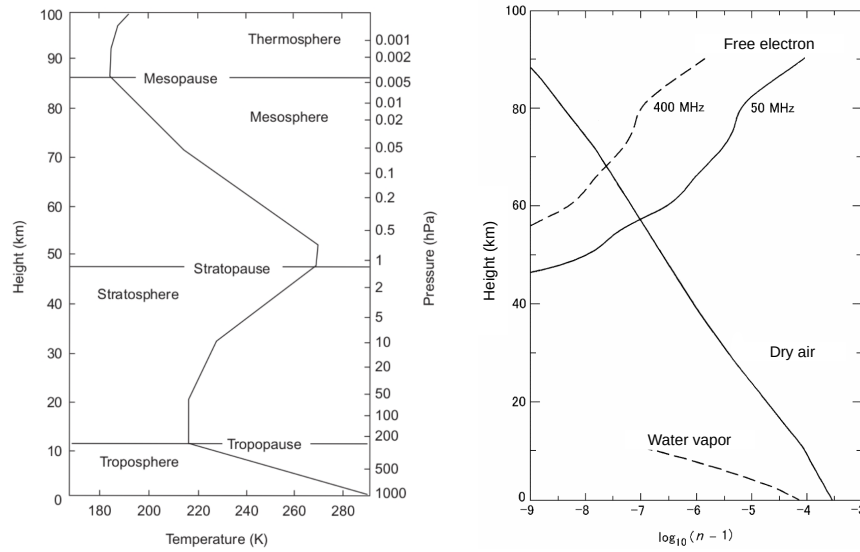


FIGURE 1.1: Temperature profile of atmosphere from U.S. standard atmosphere 1976 (extracted from Holton and Hakim [9])(left) and height profile of water vapor, dry air and free electron contributions to the radio refractive index, n (right).

It is well known that the primary source of energy within the Earth is contributed by the solar radiation from the sun. The energy that is absorbed by the Earth surface is then released upward, however, with specific propagation direction due to Coriolis effect from the Earth rotation (as in Figure 1.2), and generating various atmospheric waves. The amplitude of these waves are growing with altitude and they bring the energy and momentum before interacting with each other. The interaction of those waves with the background flow generates global-scale oscillation such as quasi-biennial oscillation (QBO) and semi-annual oscillation (SAO) [10]. The small-scale interaction which started from the lower atmosphere controls large-scale process of global circulation in the middle atmosphere, and therefore regarded as important aspect to be studied.

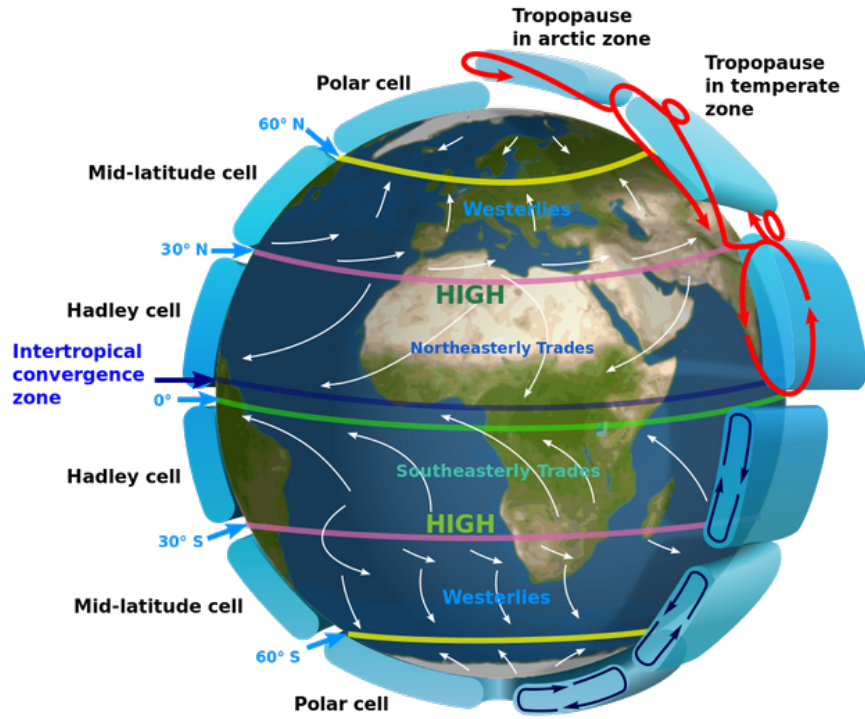


FIGURE 1.2: Illustration of the coriolis effect and its influence towards global wind flows (extracted from [11]).

There are many instruments that have been developed involving in-situ and remote sensing methods such as balloon, spaceborne radar, satellite and atmospheric radar [1]. One of the main reasons those observation techniques are developed since decades ago is to understand the dynamical processes of the atmosphere such as the one mentioned by Fukao [10]. Although solar radiation is absorbed throughout the globe, equatorial region is the only one that receive maximum energy compared to the other regions. Consequently, equatorial atmosphere has been particularly associated with the generation of most active convective motions. The motion of air, temperature, and pressure within the atmosphere are actively influenced by convective disturbance which characterized through its propagating behavior.

There are previously and ongoing studies dedicated on understanding the pattern and characteristics of the phenomena such as Kelvin waves and Rossby waves; two of the most well documented of all the wave types affecting the equatorial region [12]. Fukao [10] stated that the coupling processes in the equatorial atmosphere which incorporate hierarchical structure horizontally and vertically are poorly understood specifically due to the sparseness of the observational data in the region. Furthermore, all the processes

involved in the different layers of atmosphere were typically studied independently without a unified viewpoint which leads to a difficulty to identify the proper mechanism involved in the atmospheric changes and fluctuations.

Effort for understanding the mechanism of such phenomena requires a lot of instruments including ground-based and space-based which involves observation from several locations. These effort requires a networking of atmospheric radar that is reliable and able to continuously operate its observation. In the equator, such attempt had been executed by U.S. National Oceanic and Atmospheric Administration (NOAA) through Trans-Pacific Profiler Network (TPPN) but ended in 2002 [13]. Similar effort also had been conducted by Hashiguchi et al. [14] in Indonesia but with less sensitive radar. As the coverage for observing western Pacific region is not yet adequate, Equatorial Atmosphere Radar (EAR) was established to provide complementary and valuable observational data as demand for a larger observation coverage is escalating for a better insight of the equatorial atmosphere and its influence towards global atmosphere [13].

1.2.1 Introduction to Equatorial Atmosphere Radar (EAR)

EAR was established in 2001 by the collaboration between Research Institute for Sustainable Humanosphere (RISH), Kyoto University (formerly known as Radio Science Center for Space and Atmosphere (RASC)) and Indonesian National Institute of Aeronautics and Space (LAPAN). EAR is a VHF Doppler radar operated at 47 MHz and located at the equator at Kototabang, West Sumatra, Indonesia (0.20°S, 100.32°E (see Figure 1.3), 865 m above sea level), approximately 110 meters in diameter which consist of 560 three-element Yagi antennas. Each antenna is driven by a solid state transmitter-receiver module (TR module). The array antenna is divided into 24 groups for ease of signal distribution and maintenance where each group consists of 24 antennas except for eight groups along the periphery which contain one to three fewer antennas. These design is purposely constructed to produce a quasi-circular array pattern as shown in the Figure 1.4. Fukao et al. [13] in 2003 has elaborated in details the descriptions of EAR. It uses active phased-array system similar to the Middle and Upper atmosphere radar (MU radar) [15, 16] due to its fast beam steerability where phase shift and signal division and combination operations are carried out at a low signals level by electronic devices. Pulse compression techniques are utilized for improving signal-to-noise ratio

(SNR) without compromising the range resolution. The following Table 1.2 summarizes the specifications of the EAR.

TABLE 1.2: Specifications of EAR [13]

Item	Specification
Beam width	3.4°
Beam direction in azimuth	0 – 360° in 0.1° steps
Beam zenith angle	0 – 30° in 0.1° steps (no grating lobe)
Gain	33 dBi
Peak power	100 kW (sum of all TR modules)
Average power	5 kW (max.; sum of all TR modules)
Number of TR modules	560 units (same as Yagi antenna)
Power of single TR module	180 W
Pulse width	0.5 - 256 μ s
Inter pulse period (IPP)	200 μ s - 10 ms (variable in 200 μ s steps)
Receiver noise figure	5 dB (TR modules) - receiver type is single super heterodyne
Pulse compression	Barker, complementary and Spano codes (1 to 16 bits)
Subpulse width	0.5, 1.0, 2.0, 4.0, 8.0, 16.0 μ s (variable)
Dynamic range	70 dB
A/D converter	14 bits
Number of range gates	256 (max.)



FIGURE 1.3: Location of EAR on map.

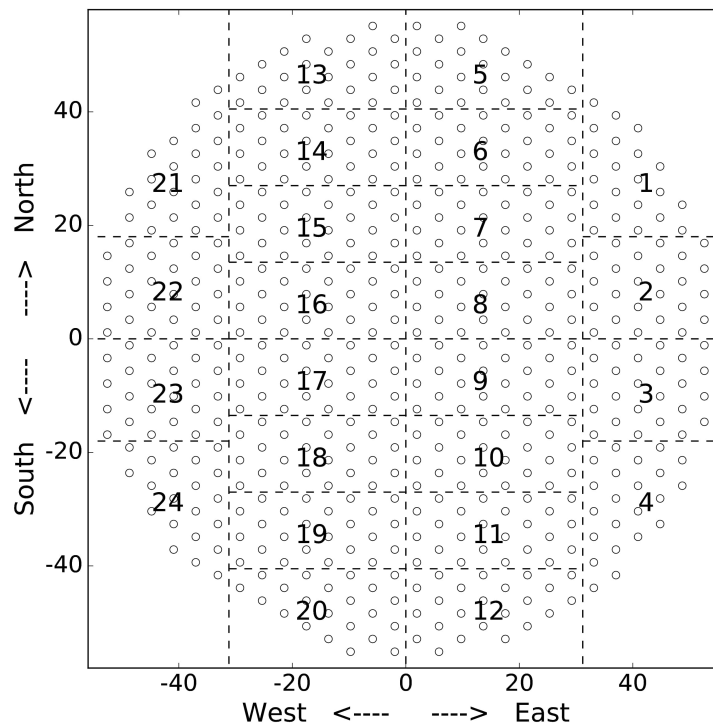


FIGURE 1.4: EAR antenna array

EAR utilizes high technology in radar observation by deploying active phased-array antenna identical to the MU radar which located in Shigaraki, Japan, also established by Kyoto University. The utilization of phased-array antenna not only enabled flexible

such advanced observation like the MU radar. With a single channel, signals from all 24 groups of the EAR antenna array are combined into a single signal before being converted into digital for further processing. By introducing multichannel, multiple radar signal from different set of antenna groups could be processed and analyzed separately, thus enable different processing technique such as spaced-antenna and spatial domain interferometry method to be implemented. There are several options to be considered when upgrading a radar system with a more advanced technology. It could be achieved by replacing the old system with a new radar hardware comprising of additional subsystems to adopt advanced observation techniques. The so called conventional method is, however, requires much resources especially in term of cost and manpower. Furthermore, it could be more favorable that such resources are channeled towards developing a new radar.

1.2.2 Software-defined radio

In order to properly address the resources constraint for upgrading a radar system, the opportunity to use software-defined method instead of a conventional hardware have to be considered. Software-defined radio (SDR) technique, in general, is a combination of general-purpose hardware, a limited hardware modification, and a special-purpose software implement signal processing. The limited hardware modification is depending on the requirements of system development, where usage of additional hardware aside from the general-purpose hardware, is required. For example, a very basic design of SDR requires an antenna to be attached in order to receive radio signal. In a bigger project such as a practical atmospheric radar, where the antenna is already existed, it might require a different set of hardware before the signal can be fed to the general-purpose hardware. Total development cost that will be contributed by the additional hardware is the key aspects to consider for the utilization of SDR.

In terms of flexibility, SDR technology is an adaptive future proof solution for wireless networks that aims to replace the conventional radio hardware by building an open-architecture based radio system software which is reconfigurable and reprogrammable. It supports different functional modules of the radio system such as modulation, demodulation, signal generation, coding, link layer protocols etc. in software [17].

One the most established platform for SDR is Universal Software Radio Peripheral (USRP) which has been developed by Ettus Research. USRP could be utilized with different software platform, but one of the most popular choices is GNU Radio. GNU Radio project is an enormous body of pre-written, free software in continuous development by a community of programmers, who have developed blocks of code in C++ to handle a wide range of signal processing functions, as well as the blocks which interface between USRP devices and the general purpose processor (GPP) [18].

1.3 Research Statements and Objectives

The main aim of this works is to develop a multichannel receiver system for EAR by adopting software-defined technique. With the aim to improve the capabilities of EAR, multichannel receiver system is to be installed alongside the existing single receiving system. Consequently, the installed multichannel receiver will be utilized to enable spaced-antenna method for estimating horizontal wind velocity which will be discussed in Chapter 3 and 4. By considering a few limitations of the multichannel receiver system, this works also aim to execute and propose the best configuration for the EAR spaced-antenna method. This topic will be discussed in detail in Chapter 4.

The scope of this thesis covers the following key points:

1. General purpose hardware and free software platform will be utilized in this works to take advantage of its flexibility in the system design. In this works, USRP and GNU Radio are chosen respectively for the mentioned purpose.
2. Full Correlation Analysis technique in time domain is used for estimating horizontal wind velocity profile from the EAR spaced-antenna method.
3. Performance of the EAR multichannel receiver will be examined based on observation test which will be conducted within the time frame of this Ph.D course.
4. Lastly, it is well recognized that EAR provides reliable observation data since 2001. Therefore, validation of the multichannel performance will be carried out by comparing with the EAR standard observation.

1.4 Thesis Outline

The first chapter of this thesis presented general introduction regarding radar theory and the research background. The objectives and scopes of this thesis are also provided. Chapter 2 provides more in-depth review of the specific topics associated, with the principle of operation for the required tools, and review of previous researches. Then, the topics regarding the software-defined radio and spaced-antenna method are explained. Chapter 3 presents the development of the multichannel receiver using software-defined radio for EAR. The configuration of the hardware and software and the processing of the data will be described in details. In Chapter 4, more analysis regarding the performance of the multichannel receiver are laid out and discussed. Comparison between different configurations of spaced-antenna that were experimented is presented, analyzed and compared with the EAR standard observation. Lastly, a concluding remarks and recommendation for future works will be provided in Chapter 5.

Chapter 2

Literature Review

This chapter presents literature review of the topics related to this research works. Previous works and researches are referred for expanding the understanding regarding the important topics, including Equatorial Atmosphere Radar, software-defined radio and its tools, and spaced-antenna method.

2.1 Review of Equatorial Atmosphere Radar (EAR)

Though equipped with a single receiving channel, EAR has great capabilities such as measuring wind field up to 20 km (e.g., see Figure 2.1 and 2.3), observing vertical profile of temperature using Radio Acoustic Sounding System (RASS), and range resolution of up to several tens of meters using frequency domain interferometry technique. Further, it can also be used for observing irregularities in the ionospheric region (100 km to 600 km). Fukao et al. [13] deliberated that, compared to the MU radar, the EAR is approximately 10 dB less sensitive. It also has fast system recovery and ease of operation and maintenance, therefore, reliable for continuous observation of the atmosphere [13]. Figures 2.1 and 2.2 show the observation results during early stage of EAR operation in 2001, extracted from Fukao et al. [13], where the horizontal wind estimated from the EAR was validated with the simultaneously operated GPS radiosondes on November 5 – 8, 2001. Further, Figure 2.3 shows the intensity plot vertical profiles of the wind were averaged over one hour for vertical, zonal and meridional components. The observation

was carried out from July to late December 2001. The results from Figures 2.1 to 2.3 show the reliability of the EAR for atmospheric observations.

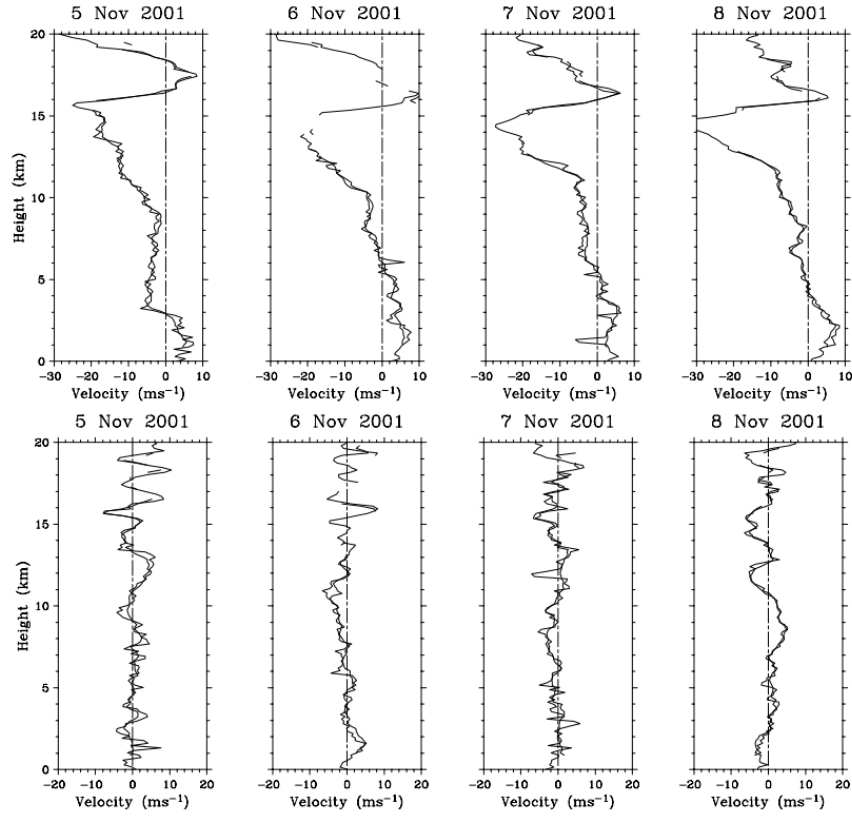


FIGURE 2.1: Comparison of zonal (upper panel) and meridional (lower panel) wind velocities from standard EAR (thick curves) and GPS radiosondes (thin curves) (extracted from Fukao et al. [13]).

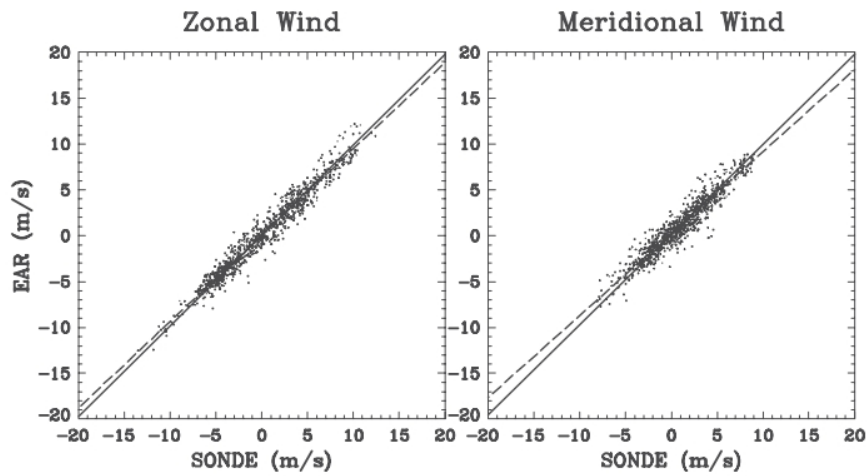


FIGURE 2.2: Scatterplots of zonal (left panel) and meridional (right panel) wind velocities from standard EAR and GPS radiosondes (extracted from Fukao et al. [13]).

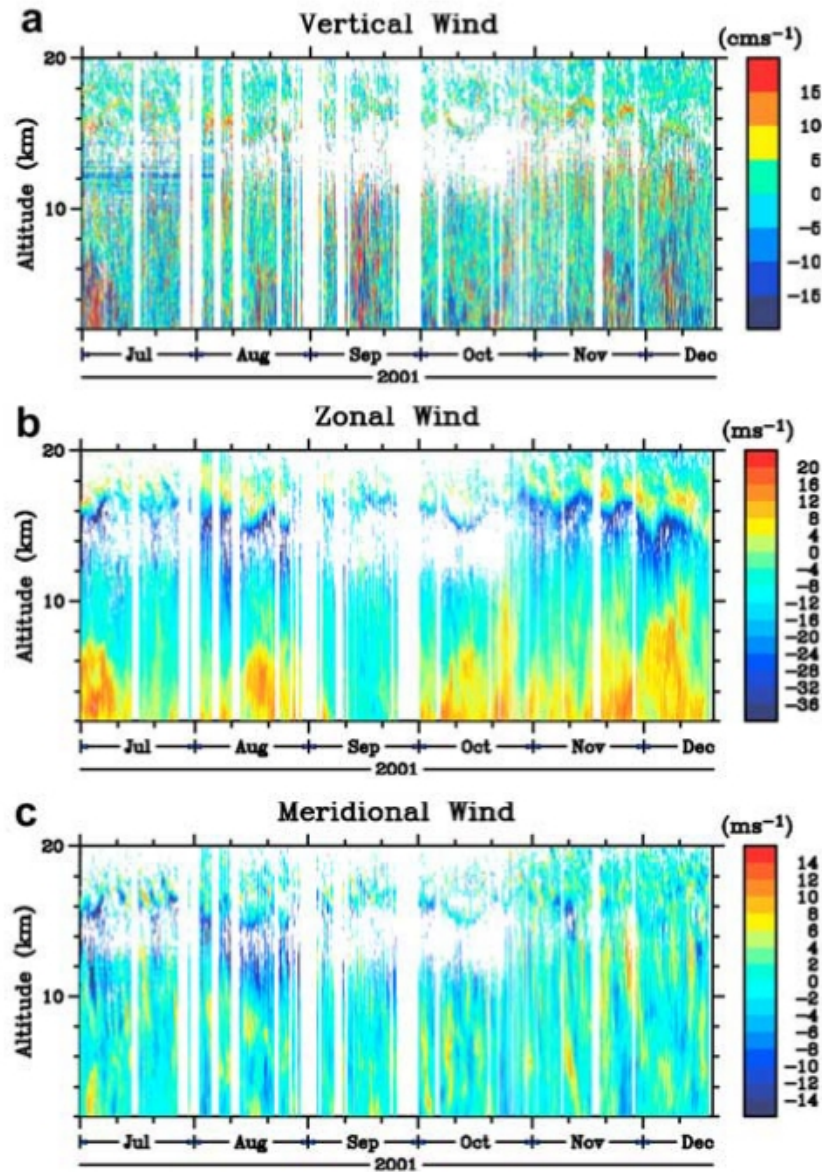


FIGURE 2.3: A sample of vertical, zonal, and meridional wind observed in 2001 (extracted from Fukao et al. [13]).

Aside from the observations during the early stage of the EAR development, there were many subsequent researches carried out, taking advantage of the EAR capabilities. One of the examples is as shown by Dhaka et al. [19] where the generation of short vertical wavelength gravity waves was identified during convective events between 12 km and 20 km height above Kototabang using combination of the EAR, 1.3 GHz Boundary layer radar (BLR) and radiosonde. The study which was conducted between April 11 – 26, 2004, used five radar beams (eastward, westward, northward, and southward with a zenith angle of 10° and vertical) and were recorded at an interval of about 3 minutes

with a vertical resolution of 150 m. Observational evidence of forcing of gravity waves with short vertical wavelength ($\sim 2 - 4$ km) was shown through relationship between the evolution of convection in the lower and middle troposphere and induced gravity waves in the upper troposphere and lower stratosphere (UTLS) region.

Another example of EAR utilization during early stage was the observation during the first campaign of the coupling processes of the equatorial atmosphere (CPEA). Seto et al. [20] observed westerly wind burst over Sumatra, Indonesia, and showed features of vertical wind and cloud distributions in Sumatra during the initial phase of a westerly wind burst (WWB) associated with a synoptic-scale super cloud cluster (SCC) which was conducted in May 5 – 9, 2004.

2.1.1 Range imaging

One of the EAR capabilities is to observe atmosphere in range imaging mode. Range imaging (RIM) is a radar technique that uses multiple frequencies to improve range resolution of a pulsed radar. The fundamental of RIM is originated by the more earlier technique, frequency domain interferometry (FDI) [21] but does not require prior knowledge of layer number and layer shape. In RIM technique, a few slightly shifted frequencies are transmitted and then the distribution of echo power within the radar volume is reconstructed [22], which enable us to reveal fine details of atmospheric structure within the radar volume. Using the EAR, one of the examples of RIM application is shown by Mega et al. [5] where the authors presented the detailed structure of Kelvin-Helmholtz instability in the tropical tropopause layer (TTL). The range imaging mode of the EAR was operated to observe turbulence with improved range resolution (down to several tens of meters). The radar beam was fixed to the vertical incidence, and five equally spaced carrier frequencies from 46.50 to 47.50 MHz (i.e., 0.25 MHz frequency spacing) were switched from pulse to pulse. The author used Capon processing method [23] to process the data at the five carrier frequencies and computed altitude profiles of echo power with a vertical sampling of 5 m. Such study shows the capability of the EAR for detailed analysis of the turbulence, comparable with other radar with multi-frequency capability (such as the MU radar).

2.1.2 Multiple receivers technique

The RIM technique in the previous subsection is able to be executed by the EAR with only a single receiver. However, the EAR could be much improved in term of variety of observation techniques if multiple receivers are enabled. Multiple receivers are described as a radar system that capable of receiving and recording atmospheric signals on two or more spatially separated antennas or groups of antennas [1]. Such attempt has been made on the EAR by Nishimura et al. [24], to extend the EAR ability using the multistatic radar observation technique. They used two additional receiver arrays located 1300 m apart from the EAR (see Figure 2.4) and successfully showed horizontal distribution of wind field over the EAR

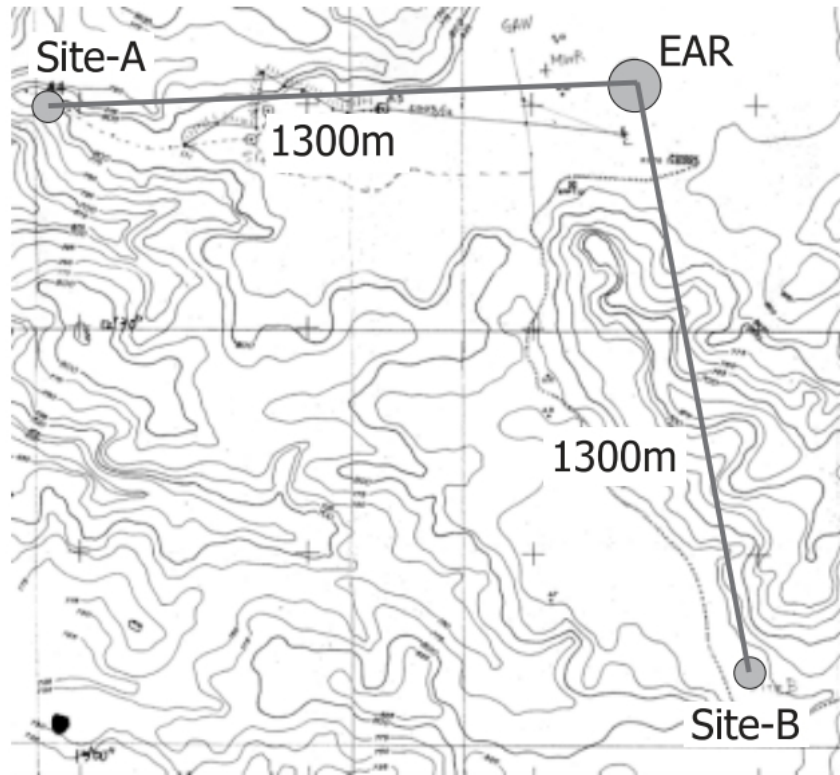


FIGURE 2.4: A plan view of the EAR and the two multistatic receiver [24].

2.1.3 Radio acoustic sounding system (RASS)

Radio Acoustic Sounding Systems (RASS) is one of the remote sensing techniques that uses a sound source to create fluctuations in the index of refraction in the troposphere and lower stratosphere. It uses the combination of radio and sound (which requires sound

source such as speaker) with an atmospheric radar to enable continuous monitoring of the temperature vertical profiles. In order to obtain strong RASS echoes, it requires Bragg condition as in the following expression to be fulfilled:

$$\vec{k}_a = 2\vec{k}_r \quad (2.1)$$

where k_a and k_r is the acoustic wavenumber vector and radio wavenumber vector, respectively. The two wavenumber vectors must be in parallel so that RASS echo is back-scattered. Since the sound wave speed is influenced by the temperature, the sound source transmit a range of frequencies so that Bragg condition is satisfied over a range of height. Doppler velocity of the RASS echoes indicates the speed of sound at the scattering volume. The speed of sound, c_s is related to the virtual temperature, T_v as follows:

$$c_s = K_d \sqrt{T_v} \quad (2.2)$$

where $K_d = 20.047$. This technique was introduced by Marshall et al. [25] and has since attracted attentions from many researchers to apply the similar technique (e.g., Matuura et al. [26], Masuda et al. [27], and Chandrasekhar Sarma et al. [28]). Recently, Juaeni et al. [29] applied the technique to the EAR and studied the effects of the acoustic source location and acoustic frequency range, as well as measurement of height profiles of temperature in the tropical troposphere. It was carried out through a test observation in 2016 where six high-power horn speakers and four subwoofers were installed to transmit the sound waves (depicted in Figure 2.5 (a)).

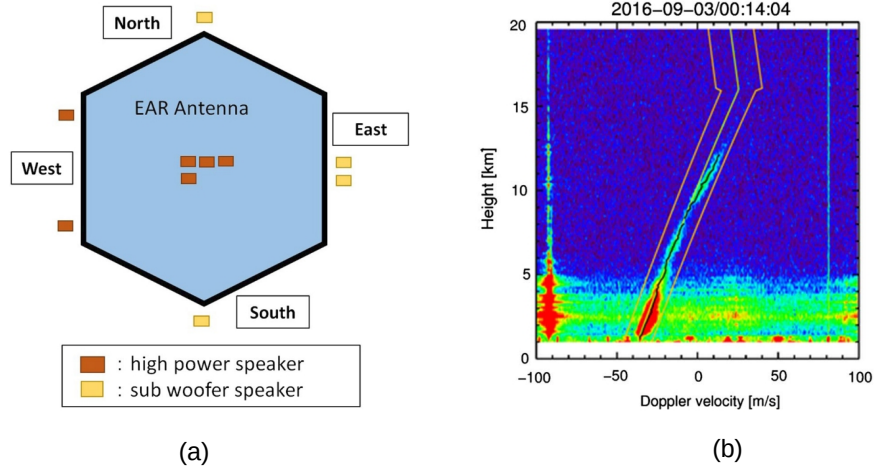


FIGURE 2.5: (a) The location of the acoustic speaker for EAR-RASS experiment and (b) The observed RASS echoes (from Juaeni et al. [29])

The authors used a three-dimensional ray-tracing method of acoustic waves to predict the shape of acoustic wavefronts, accounting for the effects of the background winds on acoustic wave propagation and selected the appropriate antenna beam directions for EAR that satisfy the Bragg condition between the radar and acoustic wave propagation vectors. Figure 2.5 (b) shows the Doppler spectrum of the RASS echoes observed on September 3, 2006 at 00:14 LT, extracted from Juaeni et al. [29].

2.2 Multichannel Receiver

This section provides more understanding regarding multiple receiver and/or multichannel receiver. As mentioned in subsection 2.1.2, multiple receiver is defined as a radar system that employs two or more spatially separated receivers where initially is mainly used for upper atmosphere (i.e., ionosphere) because the need for high-resolution atmospheric radar measurements. In fact, there are a few other techniques capable of high resolution, such as pulse compression and multiple frequency technique, which applicable to both single and multiple receiver systems and, also to a wide range of atmospheric regions. In a general sense, a multiple receiver has more advantages compared to a single receiver. In term of definition, multichannel receiver is also referred to the ability

to capture signals from two or more receivers. Therefore, both multiple receiver and multichannel receiver terms could be used interchangeably in these regards while the separation distance between the two or more receivers is not specifically defined. Hocking et al. [1] described in details about the multiple receiver technique in chapter 9 of the book. Figure 2.6 shows the illustration of the simple case principle of multiple receiver.

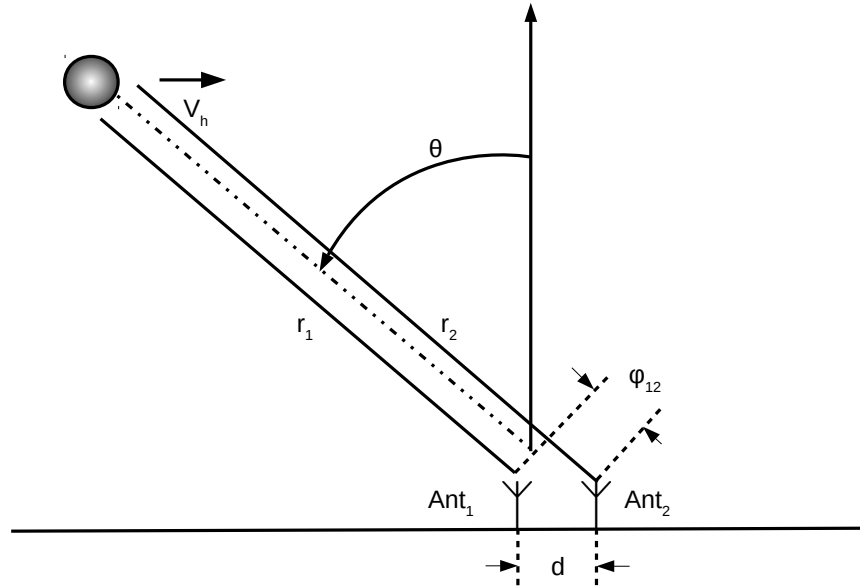


FIGURE 2.6: The principle of multiple receiver.

In Figure 2.6, return echo is scattered from a single point which is displaced by an angle, θ (measured along the baseline of the two antennas). It is received by two receivers separated by a distance, d . The phase difference, φ_{12} is then defined as, $\varphi_1 - \varphi_2 = k d \sin \theta$ where k is the wavenumber $= 2\pi/\lambda$. By measuring the phase difference where the range of the scatterer from the two antennas are known, the location of the scatterer can be determined. However, the practical radar is more complex than such simple illustration where one should consider the location of a scatterer and/or a distributed scatterer on a three dimensional coordinate system.

The implementation of multichannel receiver technique enabled sophisticated radar technique such as radar interferometry and radar imaging. Radar interferometry utilizes signal processing method to locate and track the motions of a particular scatterer or a collection of scatterers, while in radar imaging, atmospheric reflectivity fields and their velocities within a nominal resolution volume of the probing radar is reconstructed through inversion algorithm, in which spatial resolution increases [30]. The development

of a multichannel receiver provides several advantages such as enabling the spaced-antenna (SA) and spatial domain interferometry (SDI) method. Aside from imaging and interferometry, one of the significant applications of multichannel receiver is clutter rejection. For example, the adaptive beamforming is able to mitigate the ground clutter contamination to provide better accuracy of atmospheric observation (e.g. Nishimura et al. [31]). In 2004, the MU radar 29-channels digital receiver was installed to enable detailed studies of structures in the atmosphere using the radar imaging technique [32]. The multichannel system enabled the 3-dimensional imaging system on the MU radar using five frequencies over 1 MHz bandwidth between frequencies 46 MHz and 47 MHz.

There are also many works associated to multichannel development with clear advantage. In 2004, Yu and Brown [22] used spaced-antenna technique to analyze the RIM-synthesized signals and obtain high-resolution profiles of three-dimensional wind field. Their works of combined technique, termed as RIM-SA, enabled the detection of fine structures and also dynamical processes such as vertical shear.

In 2009, Yeary et al. [33] has described a multichannel digital receiver development project for the phased array radar at the National Weather Radar (NWR) testbed in Oklahoma. A single channel NWR was upgraded into eight channels for signal digitization so that it can adapt fast scanning techniques and space-antenna/interferometry measurements, which will then be used for improved weather forecasting via data assimilation. The subsequent update was presented in 2011 by Yeary et al. [34]. Latteck et al. [35] in 2012 has presented a description and first results of the middle atmosphere Alomar radar system (MAARSY) on the North-Norwegian island Andøya which is developed with operating frequency of 53.5 MHz. It has 16 channels data acquisition system which capable of interferometric applications for improved studies of the Arctic atmosphere from the troposphere up to the lower thermosphere with high spatio-temporal resolution.

In a similar effort, Sato et al. [36] in 2014, developed MST radar in Antarctic region called program of the Antarctic Syowa MST/IS radar (PANSY) to clarify the role of atmospheric gravity waves at high latitudes in the momentum budget of the global circulation in the troposphere, stratosphere and mesosphere, and to explore the dynamical aspects of unique polar phenomena such as polar mesospheric clouds (PMC) and polar

stratospheric clouds (PSC). The PANSY radar has $55 + 8$ digital receiving channels which is able for imaging and interferometry observations.

One of the significant simulation works involving multichannel system is the development of new technique to provide a generalized theoretical model of atmospheric radar imaging as described by Yu and Palmer [37]. The authors presented the development of three-dimensional (3-D) imaging technique using Capon3D and MaxEnt3D by considering four receivers and three frequencies simultaneously. Consequently, both angular and range resolution of the imaging has been improved by mitigating the limitations of beam width as well as pulse width. Such theoretical formulation is encouraging to be adapted in a practical multichannel receiver, where improvement in radar imaging resolution can be achieved.

2.3 Software-Defined Radio

Software-defined radio or SDR is a tool of radio communication system that replacing hardware equipment with a software-based system running on a microprocessor and/or FPGA.

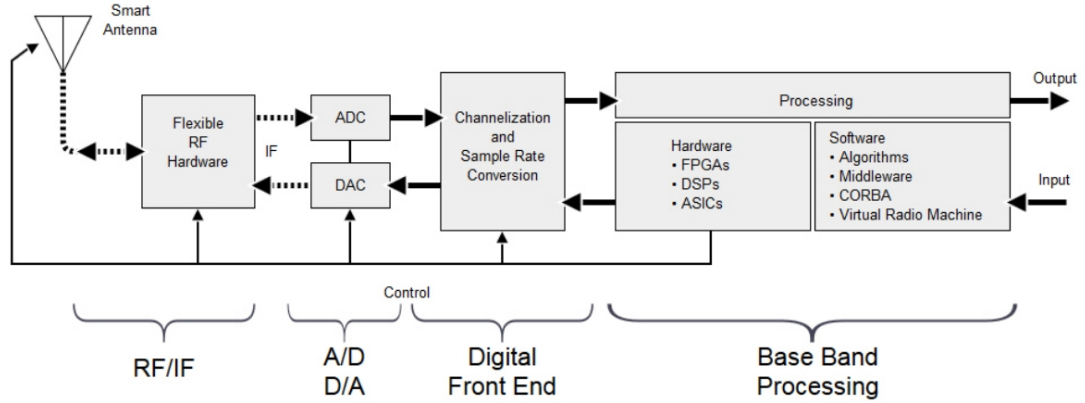


FIGURE 2.7: The block diagram of an SDR system [38].

Figure 2.7 shows the typical block diagram of a system employing software-defined radio. At the receiving point of view, the signal received by the antenna will pass through a hardware that downconvert the RF before it reach ADC for digitization. After that, the signal processing is taken care by digital acquisition system, that combines down-conversion, filtering, demodulation with FPGA-based signal processor, decimation and

further processing with a computer. The inverse, with similar processes is also occurring during signal transmission.

Generally, compared to a hardware-based system, SDR provides lower development cost. However, the cost is depending on the situation, or requirements of the system. Without a well-prepared software framework, SDR needs to be complemented with additional hardware and therefore, increase the overall development cost. The price of general-purpose hardware, on the other hand, is varied from a wide range of prices depending on its specifications. For example, the price for a very high performance USRP-2974 is about 13,455 US dollars, not included the daughterboard, and other required equipment. In comparison, a low cost alternative such as USRP B200 (board only) is priced at 771 US dollars. Therefore, careful consideration in terms of cost effectiveness, is required when choosing to work with SDR.

As a low cost alternative for radio communication system development and experiment, SDR has been widely used until present. For example, Sruthi et al. [17] was using Realtek software-defined radio (RTL-SDR) for designing a transceiver. RTL-SDR is one of the cheapest alternatives for an SDR project compared to a more established and expensive USRP. However, it has limited capabilities where the sampling rate is only 3.2 MS/s, although the operating frequencies could be used within a wide range between 64 MHz and 1700 MHz.

Back in 2011, Prabaswara et al. [39] studied software-defined FMCW radar for weather surveillance application at a frequency of 2.1 GHz and 750 kHz bandwidth for range detection of a target using GNU radio and USRP N210 as the hardware platform. It was, however, only developed as a prototype, therefore, validation of its practical performance is not available. However, it showed the opportunity of using SDR in a more advance surveillance system, such as radar. In 2013, Costanzo et al. [40] used SDR for target detection using radar. High resolution L-band radar system was developed using USRP NI2920, a software defined transceiver combined with LabVIEW. It used stretch processor technique as shown in Figure 2.8, where firstly, the radar echo signal was mixed with a reference signal of the transmitted waveform. Then, a low pass filtering (LPF) and a coherent detection are performed in order to avoid the high frequency response coming from the mixer output. Analog to digital conversion (ADC) is subsequently applied, and a bank of narrow band filters was adopted to extract the tones proportional to the

target range. Finally, a Fast Fourier Transform (FFT) is applied to derive the amplitude spectrum, whose peaks are related to the targets positions [40]. Such works were really significant in enhancing the SDR applications, where improvement in acquisition and processing is always available in line with the computing technology advancement.

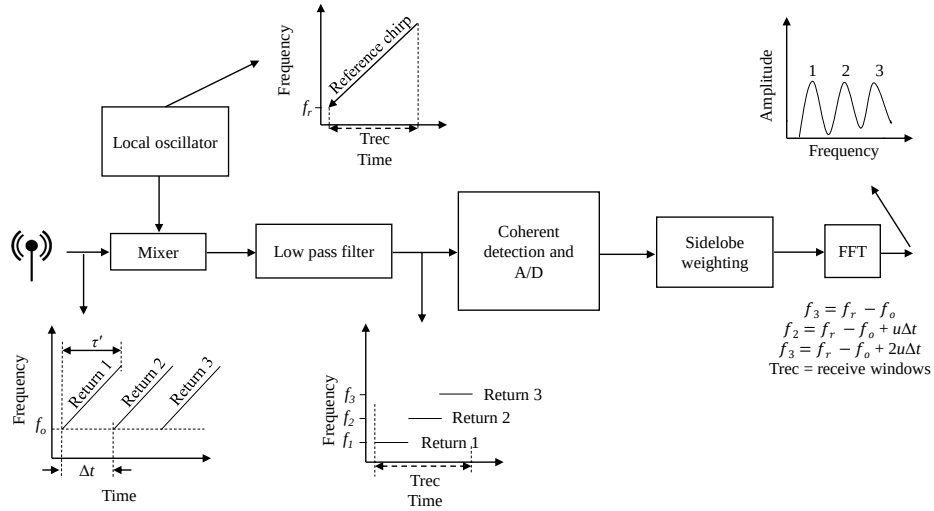


FIGURE 2.8: The block diagram of a stretch processor technique employed by Costanzo et al. [40].

2.3.1 GNU radio

There are several tools that are typically associated with SDR such as Universal Software Radio Peripheral (USRP), GNU Radio and GNU Radio companion. GNU Radio is a free and open source software development toolkit for designing a software-defined radio project, with readily available signal processing blocks. GNU radio provides the ease of development that MATLAB /Simulink provides, with better processing speed and less personal computer (PC) resource consumption. Python script can be used to control and connect the GNU radio blocks. It is also possible to develop new blocks by C++ code. The GNU radio system is developed as operating system/platform independent. Code modifications are easy since the source code is freely available and can be ported to embedded platforms. It also provides a graphical interface which is similar to the one provided by MATLAB. Although it does not support all the extensive modules as MATLAB, it does support the basic structures like signal sources and sinks. The benefits of using GNU radio over MATLAB are as follow:

1. Simplicity of programming using C++ and Python.
2. Does not have resource hungry UI interfaces during runtime.
3. Runs on Linux and Windows with not much code changes.
4. Basic blocks are developed in C++ so that they provide the real time performance that is needed to interface with the USRP.

2.3.2 GNU radio companion

GNU radio companion (GRC) is a graphical tool for creating signal flow graphs when designing a software-defined radio project. Blocks are manually integrated into GRC via descriptive python definitions. The definitions are very flexible, and allow multiple GNU Radio blocks to be grouped into a single GRC super-block. GRC provides a graphical user interface to the user so that hardware functions like mixers, oscillators, and more others, can be implemented as a block and can be executed. These blocks use Python code to define its functioning (at the background) and xml code for creating GUI (in the foreground). A block is actually a class implemented in C++ language. Simplified wrapper and interface generator (SWIG) is used as an interface between C++ and python, thus python sees each block as a separate class defined in their respective module.

Then the next step is to create suitable xml code for developing the code into a real block. Any operations that are being carried out using hardware can also be executed similarly using GRC. However, the constraint here is to place the blocks sequentially and making sure that all the parameters are defined properly. Several prewritten blocks are available which are developed mainly based on commonly used functions. In most cases, if the application demands for some additional blocks other than the available, the parameters of the existing blocks can be changed according to the requirement and saved as separate blocks. This type of blocks developed from the existing blocks is called the Hierarchical blocks. Second method, is to write a Python code based on required specifications and suitably generating an XML file, where it describes the block's parameters, inputs, outputs, and other attributes. This type of block is called as custom block [41].

2.3.3 Universal software radio peripheral

Universal software radio peripheral (USRP) is a range of software-defined radios designed and sold by Ettus Research and its parent company, National Instruments. Developed by a team led by Matt Ettus, the USRP product family is intended to be a comparatively inexpensive hardware platform for software radio, and is commonly used by research labs, universities, and hobbyists. The USRP has high speed hostlink, i.e. Gigabit Ethernet, which is used to connect to a host machine. The host machine then uses software to implement the entire signal processing functions in the radio. These functions can also be loaded on to the onboard FPGA for faster execution.

2.3.4 USRP hardware driver

The USRP Hardware DriverTM (UHD) software API supports application development on all USRP SDR products. Using a common software interface is critical as it increases code portability, allowing applications to transition seamlessly to other USRP SDR platforms when development requirements expand or new platforms are available. Hence, it enables a significant reduction in development effort by allowing the users to preserve and reuse their legacy code so that focus can be directed towards developing new algorithms. More detailed information could be read on Ettus research knowledge-based article on UHD [42]. UHD also offers cross-platform support for multiple industry standard development environments and frameworks, including RF network on chip (RFNoC), GNU Radio, LabVIEW and Matlab/Simulink. It is also available on Linux, Windows, and Mac OS to ensure the users have no restrictions on using UHD.

2.4 USRP Architecture

While some characteristics and specifications vary from model to model, all USRP devices use the same general architecture. In many cases, the RF frontend, the mixers, filters, oscillators and amplifiers required to translate a signal from the RF domain and the complex baseband or IF signals. The baseband or IF signals are sampled by ADCs, and the digital samples are clocked into an FPGA. The stock FPGA image provides digital down-conversion functionality, which includes fine-frequency tuning and several

filters for decimation. After decimation, raw samples or other data are streamed to a host computer through the host interface. The reverse process applies to the transmit chain. The bandwidth of the USRP device varies at each point in the signal chain. Three general types of bandwidth specifications are the analog bandwidth, the FPGA processing bandwidth, and host bandwidth. The system bandwidth is generally the minimum of the RF daughterboard, FPGA processing, and host bandwidth. Care should also be taken to avoid an analog bandwidth that is greater than the ADC/DAC sample rate of any device.

2.4.1 USRP types

An SDM receiver system for EAR was developed using Universal Software Radio Peripheral (USRP), which is a general-purpose hardware platform typically used for software-defined radio. There is a variety of USRP devices with different advantages and limitations.

TABLE 2.1: Types of USRP and its general specifications

USRP Model	Connectivity	Frequency range	Daughterboard
E3xx	microUSB and 1 GigE	70 MHz - 6 GHz	-
N2x0	Gigabit Ethernet (GigE)	DC - 6 GHz	1 slot
B2xx	USB 3.0	70 MHz - 6 GHz	-
N3xx	1 GigE and 10 GigE	10 MHz - 6 GHz	-
X3x0	USB 3.0, 1 GigE, 10 GigE and PCIe	DC - 6 GHz	2 slots

Table 2.1 shows the general specifications of the available USRP devices for software-defined radio project. The model is further divided into a few types from each series which representing different detail specifications and performance. Each model is designed to be used for a wide range of applications and is distinguishable through its series name, where, E stands for embedded-series, N for networked-series, B for bus-series, and X series is for high performance applications. The frequency range of the USRP is strictly depending on the type of daughterboard used except for the type that already has integrated board such as E, B and N3x0 series.

2.4.2 Motherboard

A motherboard provides the following subsystems: clock generation and synchronization, FPGA, ADCs, DACs, host processor interface, and power regulation. These are the basic components that are required for baseband processing of signals. In a typical case, it provides reference clock to the daughterboards, which the daughterboards will use to generate LO signals. Some USRP products also contain an electrically erasable programmable read-only memory (EEPROM) on the motherboard which is used to store information about the USRP, such as product code, revision number, USRP name, and IP address. The specific information stores on each USRP EEPROM is dependent on the USRP model. Currently, the N200/210, X300/310, B200/210, and E100 contain an on-board EEPROM.

2.4.3 Daughterboard

A modular front-end, called a daughterboard, is used for analog operations such as up/down-conversion, filtering, and other signal conditioning. This modularity permits the USRP to serve applications that operate between DC and 6 GHz. After selecting a daughterboard based on frequency coverage, users must also ensure that the daughterboard meets the bandwidth requirements for the application of interest. Most of the transceiver daughterboards provide 40 MHz or 120 MHz of instantaneous RF bandwidth in both the transmit and receive directions. The ability to utilize the full bandwidth depends on the USRP device that the daughterboard is paired with, and the resolution of the data transferred over the host interface. Table 2.2 shows the type of available daughterboards and its general specifications [42].

TABLE 2.2: Types of USRP daughterboard and its general specifications

Daughterboard	Frequency range	Feature	Bandwidth
LFRX	0 - 30 MHz	Receive only	30 MHz/channel
LFTX	0 - 30 MHz	Transmit only	30 MHz/channel
BasicRX	1 - 250 MHz	Receive only	100 MHz/channel
BasicTX	1 - 250 MHz	Transmit only	100 MHz/channel
WBX-40	50 MHz - 2.2 GHz	Receive and transmit	40 MHz
WBX-120	50 MHz - 2.2 GHz	Receive and transmit	120 MHz
SBX-40	400 MHz - 4.4 GHz	Receive and transmit	40 MHz
SBX-120	400 MHz - 4.4 GHz	Receive and transmit	120 MHz
CBX-40	1.2 GHz - 6 GHz	Receive and transmit	40 MHz
CBX-120	1.2 GHz - 6 GHz	Receive and transmit	120 MHz
UBX-40	10 MHz - 6 GHz	Receive and transmit	40 MHz
UBX-160	10 MHz - 6 GHz	Receive and transmit	160 MHz

For usual purpose, the WBX, SBX and UBX transceiver daughterboards are a good choice because they provide full-duplex capability with bandwidth that is more than sufficient for many applications. One important thing to consider is the bandwidth capability of the USRP device selected. While a daughterboard may provide up to 40 MHz of the RF bandwidth, this does not guarantee the USRP device can transfer an equal bandwidth to the host machine. If a user requires a specific maximum bandwidth, they should ensure that the daughterboard, USRP device and the host computer meet those requirements. Further reading and details regarding the suitable daughterboard for a different type of USRP devices could be read from Ettus research knowledge base online [42].

2.5 Spaced-Antenna Method

Spaced-antenna (SA) method is considered as one of the radar techniques in atmospheric observations field, which uses two or more spatially separated receiving antennas. SA method is also addressed as spaced antenna drift technique (e.g., Hocking [43] and Kumar et al. [44]) and falls under a more broader term, multi-receiver radar technique.

One of the techniques that uses SA method is Postset Beam Steering (PBS) [45, 46]. Although PBS is also falls under multi-receiver radar technique, it is well suited to be categorized as a signal processing technique that utilized SA method. Although, different terms are used to describe the methods and techniques, it does not lead to confusion as long as the definitions are clear and well understood. Hocking et al. [1] discussed concisely in one of the chapters about the multiple-receiver radar technique, including the SA methods. Fundamental discussions regarding SA method could be traced back to the original papers by Mitra [47] and Briggs et al. [48]. The underlying concept of SA method is originated from the recorded radio wave echoes collected from multiple receiving antennas. The echoes are reflected due to atmosphere's irregularity which consequently produce irregular diffraction pattern on the ground. These patterns appear as amplitude fading in time-domain where theoretically, the fading at each receiving antennas would be similar, but displaced in time [48]. Such time displacement, or time delay, τ , occurs due to the movement of the moving pattern over a group of receiving antennas, which can be measured by correlating the signals from each antennas. A simple case for understanding SA method concept is depicted in Figure 2.9, where two spatially separated receiving antennas measured backscattered signal at a slightly shifted time and the corresponding cross-correlation produced time delay, τ which is used for monitoring the wind speed aloft.

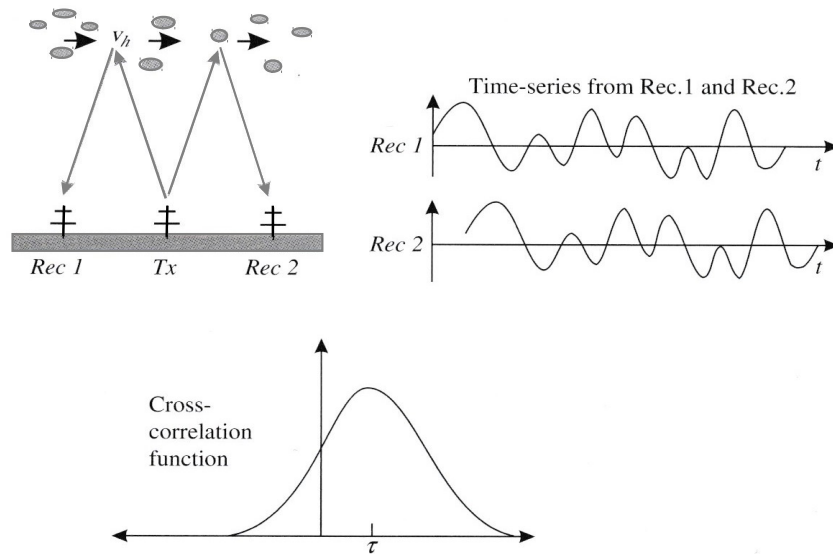


FIGURE 2.9: Correlation function on a simple spaced antenna for monitoring wind speed aloft

Although SA method was originally designed for measuring upper atmosphere's winds, its application has been utilized for a wide range of atmospheric regions. For example, Yamamoto et al. [49] analyzed the horizontal structure of the scattering pattern in the mesosphere using full correlation analysis on the MU radar in 1989. The observation range was conducted between 60 km to 98.1 km. Ramkumar et al. [50] in 2010 carried out simultaneous measurements of zonal drift velocities, observed in the heights of 84 – 98 km in the Indian geomagnetic dip equatorial region by a medium frequency (MF, 1.98 MHz) spaced-antenna, along with a high-frequency (HF, 18 MHz) Doppler radars. Later in 2014, on a different atmospheric region, Dolman and Reid [51] described the performance of boundary layer wind profiling radar adopted by the Australian Government Bureau of Meteorology using SA method. The authors successfully implemented quality control and hardware improvements to minimize internal clutter through empirical correction method.

In 2012, Lindseth et al. [52] developed portable 449-MHz wind profiler radar using SA method to measure horizontal wind up to 4 km altitude. Long before that, in 2001, Cohn et al. [53] used SA method on multiple antenna profiler radar at 915 MHz at boundary layer (below 2 km). Then, in 2007, Zhang and Doviak [54] discussed the theory and formulation of spaced-antenna interferometer to measure wind, shear and turbulence using phased-array weather radar. In 2013, Kumar et al. [44] described the estimation of horizontal winds using spaced-antenna drift technique on the MU radar with improved observable height of up to 20 km. The aperture size of each receiving antennas was approximately one third of the whole MU radar. The authors used an orientation that is constantly rotating four times in a cycle throughout the observation and produces an average estimation after each cycle.

There are a few advantages of applying SA method in radar observations. One of the examples, it could be applied with a simple antenna topology while adding some processing and receiver complexity [52]. Under basic operation, SA method provides better time resolution compared to Doppler beam swinging (DBS) method due to having only a single beam to be processed [52]. Further, SA method has larger signal to noise ratio compared to DBS in the presence of stable layer [46]. In demonstrating its capabilities, Kumar et al. [46] in 2016 has utilized SA method on the MU radar to obtain horizontal winds and eddy dissipation rates, which were then compared with postset beam steering technique where the agreement is good up to 16 km altitude. In 2001, Hobbs et al. [45]

compare SA method with DBS method which indicated good agreements between both techniques.

However, there is no technique without any disadvantages. For example, SA method is well known to produce underestimation of the wind magnitude compared to independent data source such as radiosonde [51]. Few researches also suggest that the antenna spacing should not be too small since wind underestimation occurred because the triangle size is too small. In a paper published in 2014, Dolman and Reid [51] discussed the issue known as wind magnitude underestimation and corrected for wind underestimation by SA method on boundary layer profilers by applying quality control to the 30-min average wind data so that it can be utilized for forecasters. Another example of disadvantages of SA method is, the signal-to-noise ratio is typically lower than with DBS (empirical observations suggests that SA method has a 10 dB lower SNR), which uses the first moment while FCA uses higher order moments [52]. However, such weaknesses have not significantly limit the applications of SA method, as long as the purpose is achieved, and for a long term, the revelation allows for more researches to be conducted for improvement of the technique.

Chapter 3

Development of Software-Defined Multichannel Receiver

This chapter presents the works that were being carried out for developing multichannel receiver system for EAR. Configuration of the hardware and software, and the signal processing are explained in detail.

3.1 Introduction

EAR which has been established since 2001 has long provided significant data from observations over the equatorial atmosphere. Advantages of the EAR are good altitude resolution (~ 150 m), ability to measure wind field up to 20 km, ability to steer the antenna beam on a pulse to pulse basis electronically, and ability to use RASS to measure altitude profiles of temperature. They are all achieved with a single receiving channel. There are, however, a number of advantages to have multichannel receiver system such as the one for the MU radar in Shigaraki, Japan. One example of their advantages is the ability to use spaced-antenna and spatial domain interferometry method.

3.2 Multichannel System Configuration

There are several types of USRP that allow synchronization of multiple channels, such as X3x0 and N2x0 series. In terms of performance, USRP X3x0 holds advantages over

USRP N2x0 series. Several requirement considerations could be laid for choosing one model, but the key aspects are cost and performance. Two models available within the high performance X-series are USRP X300 and USRP X310. Although USRP X310 holds more powerful FPGA, however, it is more expensive. As our application does not require higher performance FPGA, we selected USRP X300. The front and rear interface of the USRP X300 is shown in Figure 3.1.



FIGURE 3.1: Front and rear interface of USRP X300

3.2.1 USRP X300

The Ettus Research USRP X300 is a high-performance, scalable software-defined radio (SDR) platform for designing and deploying next-generation wireless communications systems. The hardware architecture combines two extended-bandwidth daughterboard slots covering DC – 6 GHz with up to 160 MHz of baseband bandwidth, multiple high-speed interface options (PCIe, dual 10 GigE, dual 1 GigE), and a large user-programmable Kintex-7 FPGA in a convenient desktop or rack-mountable half-wide 1U form factor. USRP X300 shows best-in-class hardware performance. Through UHD software application program interface (API), it is compatible for cross-platform development and is available on Linux, Windows, and MacOS [55]. Figure 3.2 shows the block diagram of USRP X300 provided by Ettus Research. Almost all components in the motherboard are controlled by the FPGA. USRP X300 supports two daughterboards, to ensure smooth operations of signal receptions. Modification of the FPGA, however, is not recommended to any USRP due to its significance and effect to the whole operation of the USRP devices. Alan John Jones [56] presented in his Master's thesis, the modifications effort to the FPGA, but was not successful. There is exception for a few types that has been equipped with special processing tool, namely, RF network on

chip or RFNoC, which enabled FPGA modification to move the processing of IQ signal to the FPGA before being transferred to the computer. This, consequently, reduce the processing load by the computer, which will significantly improve the performance of, as an example, multichannel systems.

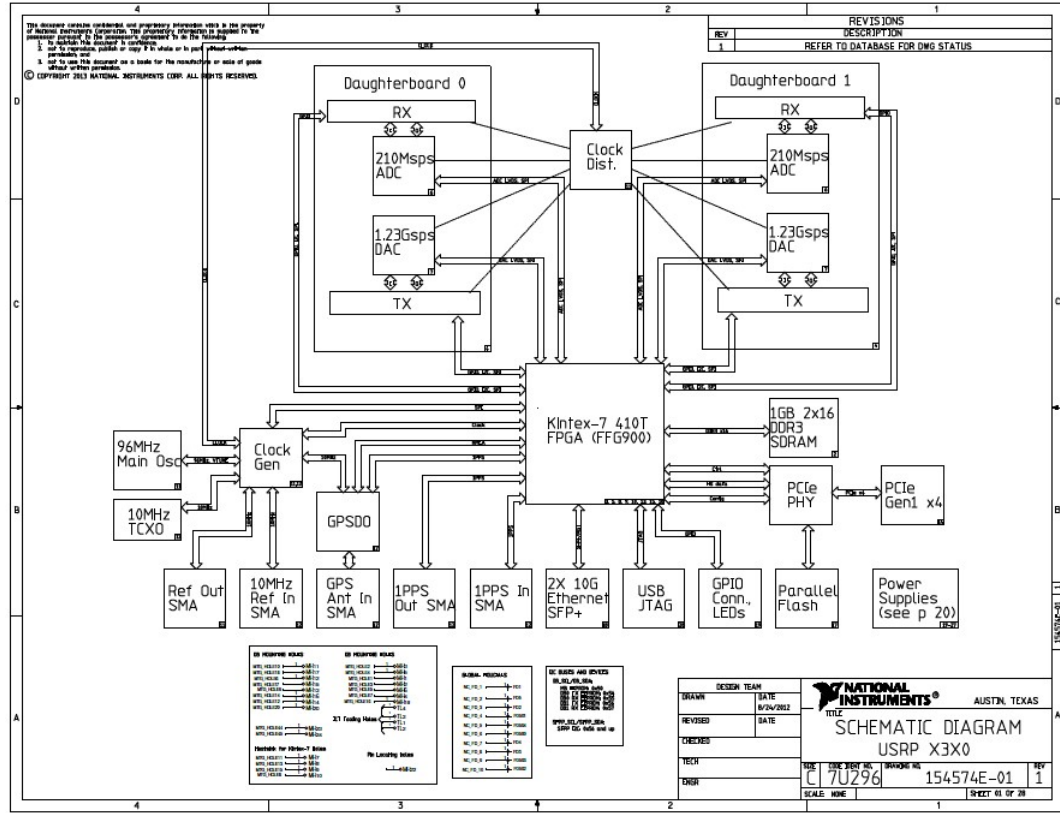


FIGURE 3.2: Block diagram of USRP X300

In general, the USRP X300 can receive and transmit two channels each and is supported with high speed 1 Gigabit ethernet (GigE) and a 10 GigE port (both are established as enhanced small form-factor pluggable transceiver (SFP+)) located in the rear panel of the device. Both SFP+ ports on the X300 can be utilized as 10 GigE ports simultaneously, the firmware for this is available within the USRP hardware driver (UHD) software distribution.

3.2.2 Hardware setup

The current development of an SDM receiver for EAR utilizes two USRP X300s and a personal computer (PC). The key technology embedded in the USRP X300 is a field

programmable gate array (FPGA) that is able to handle a constant stream of high-speed data. The in-phase and quadrature-phase signals (henceforth called IQ signals) are produced by the digital down conversion from IF to baseband by the FPGA on the USRP motherboard. The IQ signals are further processed through low pass filtering, and down-sampling. In this study, each USRP X300 is equipped with two BasicRX daughterboards (Figure 3.3) that can receive radio frequency (RF) signals between the range of 1 MHz to 250 MHz. This is well suited to the EAR operating frequency of 47 MHz. The link between the device and the host computer is established through the 10 GigE port. To enable the multichannel receiver system, multiple USRP X300s are synchronized using a 10 MHz reference clock and a 1 pulse per second (PPS) signal, distributed from a single OctoClock CDA-2990 device (Figures 3.4 and 3.5).

3.2.3 BasicRX

The BasicRx daughterboard (Figure 3.3) is a low-cost daughterboard that provides direct access to the ADC inputs. The board can accept real-mode signals from 1 to 250 MHz. The BasicRx is ideal for applications using an external front end providing relatively clean signals within operable bandwidth. Wideband transformers couple each RF input to a single channel of the USRP device's ADC. The signals sampled by the ADC are manipulated in the FPGA, and can be processed as two real-mode signals, or a single I-Q pair.

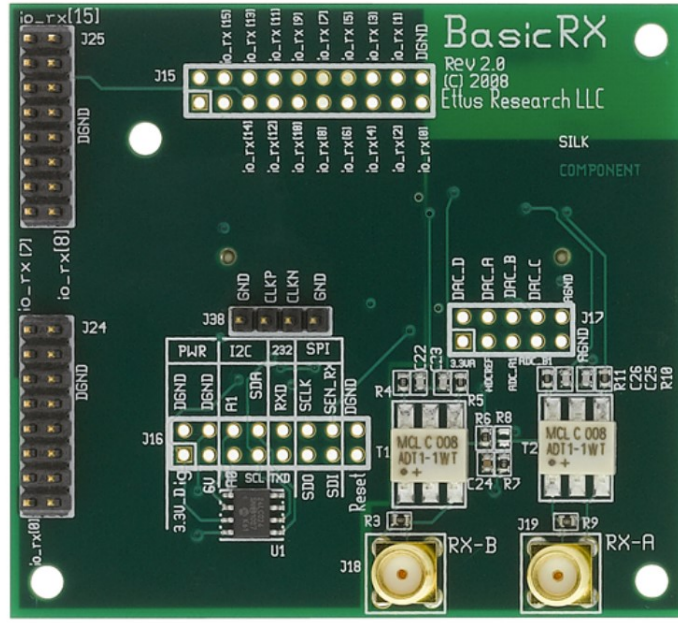


FIGURE 3.3: Image of BasicRX daughterboard

3.2.4 Octoclock CDA-2990

The OctoClock CDA-2990 is an affordable solution for high-accuracy time and frequency reference distribution. This is a useful accessory for users that would like to build multi-channel systems that are synchronized to a common timing source. The interface is as shown in Figure 3.4. For example, the OctoClock CDA-2990 can be used to synchronize a system of USRP N210s for coherent operation. This is useful for many applications such as beamforming, direction-finding, diversity combining, or MIMO transceiver design.

The OctoClock CDA-2990 accepts one pulse-per-second (1 PPS) and 10 MHz reference inputs from an external source. Active components are used to amplify and distribute these signals with matched-length traces to 8 outputs. In our works, 10 MHz and 1 PPS signals are generated by the EAR timing board. The multichannel receiver system is then synchronized to the existing EAR.



FIGURE 3.4: Interface of Octoclock CDA-2990

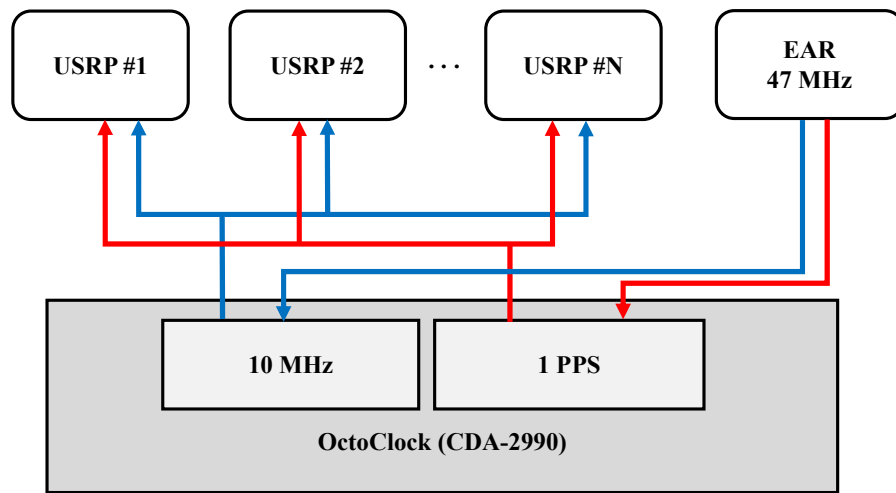


FIGURE 3.5: Illustration of multi USRP configuration

3.2.5 Software setup

One of the most established options for a software-defined radio project is GNU Radio. GNU Radio is a free and open source software development toolkit that provides signal processing blocks specifically for the development of SDR. To provide easy handling of the software, a GNU radio companion (GRC) was used as a graphical tool to allow system designs to be visualized as a network of block diagrams. Output from GRC is a Python code with GNU radio functions. In general, GNU Radio acts as a software platform for the receiver that controls the USRP devices through a UHD. Signal processing in GNU Radio is carried out by a network of signal processing blocks. Each block handles one signal processing operation (such as filtering, multiplication, and addition) inside

a flowgraph. The data passes through the flowgraph and is called an item, which can be represented by any data type, such as integer, complex and float. The processing inside a single block is achieved using the C/C++ programming language, which enables smooth and high speed signal processing.

Execution of a complete flowgraph through GRC generates a Python code. This will allow users to modify the program based on their needs and requirements. Furthermore, GNU Radio allows users to create their own signal processing blocks, using either C/C++ or Python. Program integration between different programming languages is realized by the Simplified Wrapper and Interface Generator (SWIG). Details of the GNU Radio can be found online at GNU Radio [57]. To avoid system error, the UHD version was updated to match the USRP devices and its corresponding FPGA images. In this study, the installed version of the GNU Radio was 5.4.0 with UHD version 3.10.2.0 and was accompanied by GRC version 3.7.11.1. GRC simplified the setup of the synchronized multiple channels through a UHD USRP source block where known parameters such as the number of motherboards and number of channels needs to be provided. We also set the output format to be complex float32, and the USRP motherboard clock source and time source was set to external because we were using an OctoClock device to synchronize the channels.

3.2.6 Phase difference between channels

The performance of a multi-channel receiver for EAR depends on the synchronization of all receiving channels. We therefore analyzed the phase difference between all channels using a signal generator that produces a 47 MHz sine wave. This is identical to the configuration shown in Figure 3.5, in which the signal is split and fed into the four channels from the two USRP X300 devices except the EAR is replaced by the signal generator. The measurement was taken repeatedly for a few times and the duration for each measurement was about 10 minutes. After each measurement, the devices were turned off to observe if any offset due to the device itself existed. The recorded data are shown in Table 3.1.

TABLE 3.1: Average and standard deviation of the phase difference between channels

Channel	Average (<i>rad</i>)	Standard Deviation (<i>rad</i>)
<i>Ch.1</i> vs <i>Ch.2</i>	-0.01237	0.00090
<i>Ch.3</i> vs <i>Ch.4</i>	0.01744	0.00074
<i>Ch.1</i> vs <i>Ch.3</i>	-0.00977	0.00091
<i>Ch.1</i> vs <i>Ch.4</i>	0.00797	0.00090
<i>Ch.2</i> vs <i>Ch.3</i>	-0.00004	0.00074
<i>Ch.2</i> vs <i>Ch.4</i>	0.01580	0.00074

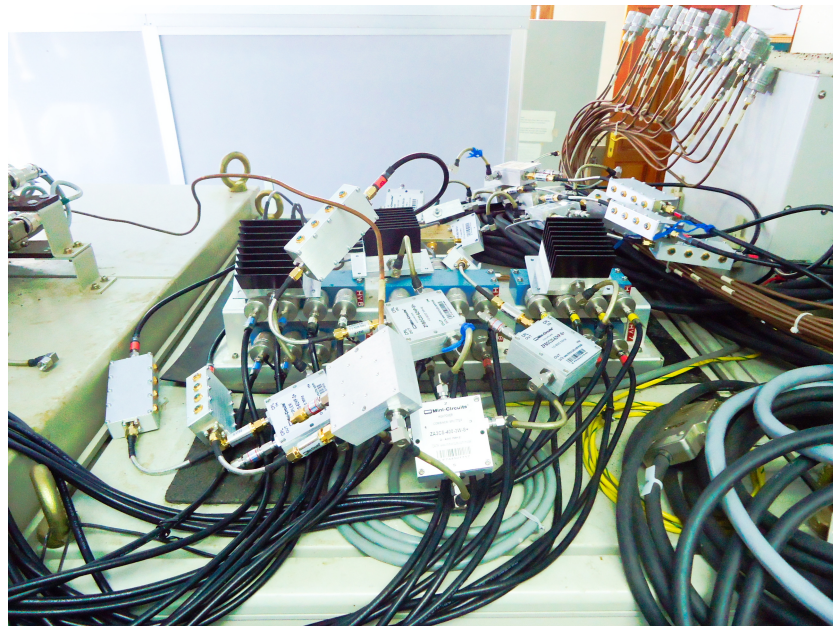
A single motherboard of USRP X300 supports two channels. Therefore, throughout the test we consistently mapped Channels 1 and 2 for a single USRP X300 and Channels 3 and 4 for another single USRP X300. In summary, we measured all the channels within the same motherboard and across different motherboards for this analysis. From the test, we found that the maximum phase difference was less than 0.02 radians, regardless of which motherboard the channel originated from. This value corresponds to less than two centimeters in real measurement of EAR. This performance could be considered adequate for a real observation. We also found that there was no offset originating from the device and therefore, no calibration was required.

3.3 Observation System

To analyze the reliability of the multi-channel receiver system, we conducted test observations using EAR on November 30, 2017, March 7, 2018, and July 14, 2018. Figure 3.6 shows the images taken from the indoor observation site of the EAR.



(A) The equipments used during the experiment



(B) Directional couplers and power divider-combiners used during the experiment

FIGURE 3.6: Images from EAR indoor observations site.

The general test observation system is configured as in Figure 3.7. Antenna groups from EAR is modified so that, the signals can be distributed to the multichannel receiver from directional coupler. Figure 3.8 shows the modification to the antenna groups connection compared to the original configuration. Analog 2-to-1 combiner are used to combine signals from groups 6 and 7 (Channel 1), groups 10 and 11 (Channel 2), and groups 22 and 23 (Channel 3), while another directional coupler is used to combine all groups signal (for Channel 0). Figure 3.9 shows more detail configuration of the SDR receiver used in this work. The complex received signal from EAR in terms of voltage, $V(r, t)$ can be expressed as:

$$\begin{aligned} V(r, t) &= A \exp \left\{ j \left[2\pi f_0 \left(t - \frac{2r}{c} \right) + \varphi_0 \right] \right\} U \left(t - \frac{2r}{c} \right) \\ &= A \left[\cos \left(2\pi f_0 t - \frac{4\pi r}{\lambda} + \varphi_0 \right) + j \sin \left(2\pi f_0 t - \frac{4\pi r}{\lambda} + \varphi_0 \right) \right] U \left(t - \frac{2r}{c} \right), \end{aligned} \quad (3.1)$$

where A is the echo amplitude, the cosine and sine are the real and imaginary part of $V(r, t)$ oscillating at the carrier frequency, f_0 , t is time when the echo is received after pulse transmission, φ_0 is the initial phase of the transmitted signal, and $2\pi f_0(t - 2r/c) + \varphi_0$ is the echo phase. The pulse function $U(t - 2r/c)$ is unity when its argument $t - 2r/c$ is between 0 and τ , and is zero otherwise. Then, the IQ signal produced from USRP are expressed as:

$$I(r, t) = A \cos \varphi U \left(t - \frac{2r}{c} \right), \quad (3.2)$$

$$Q(r, t) = A \sin \varphi U \left(t - \frac{2r}{c} \right), \quad (3.3)$$

where the echo phase is defined as $\varphi = -4\pi r/\lambda + \varphi_0$.

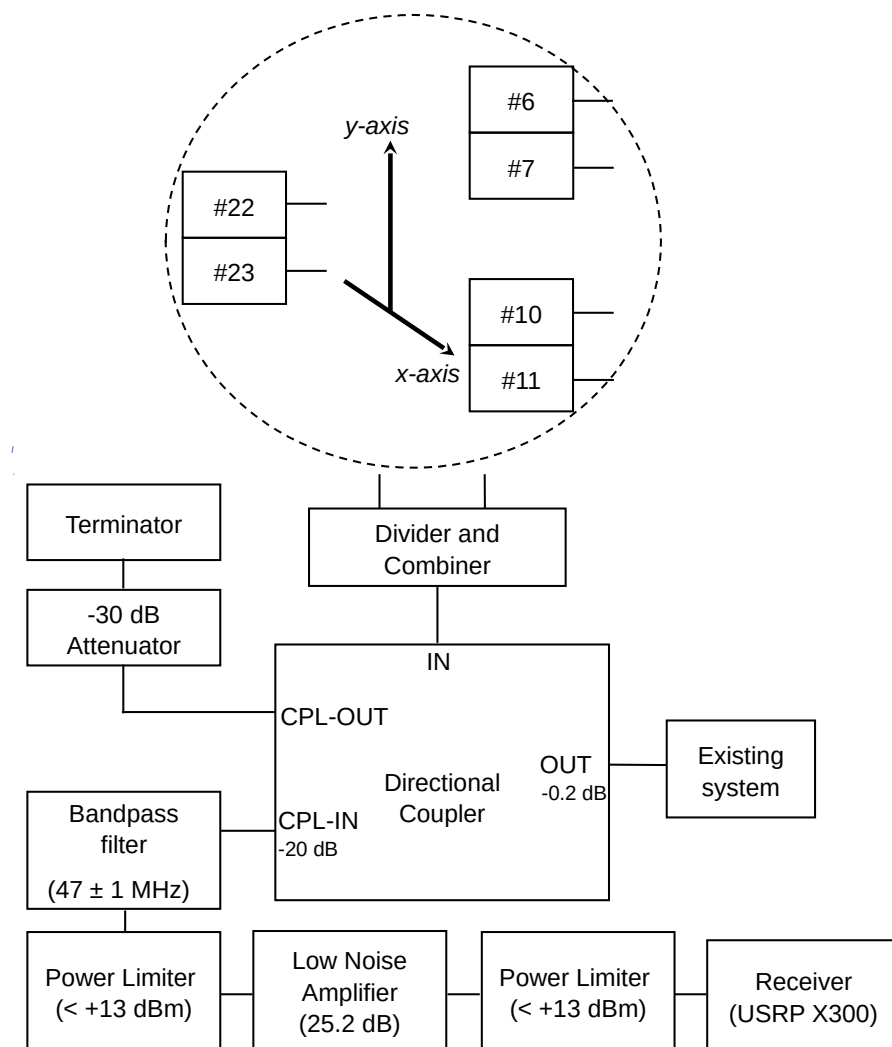


FIGURE 3.7: Configuration of test observation.

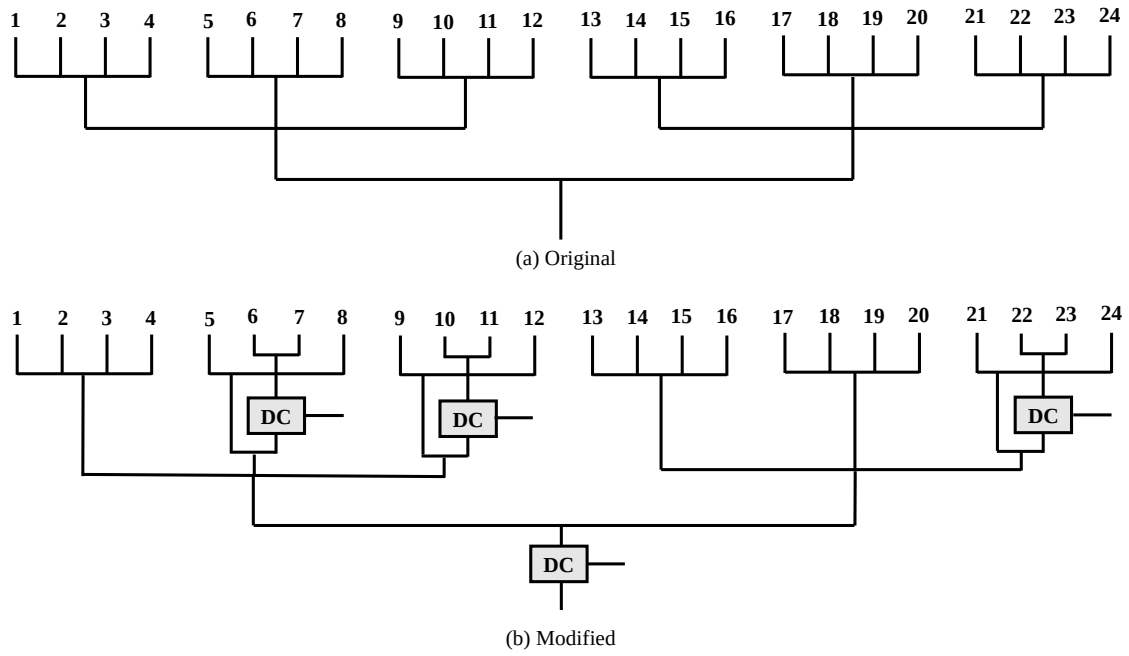


FIGURE 3.8: Modification to the EAR antenna groups connection.

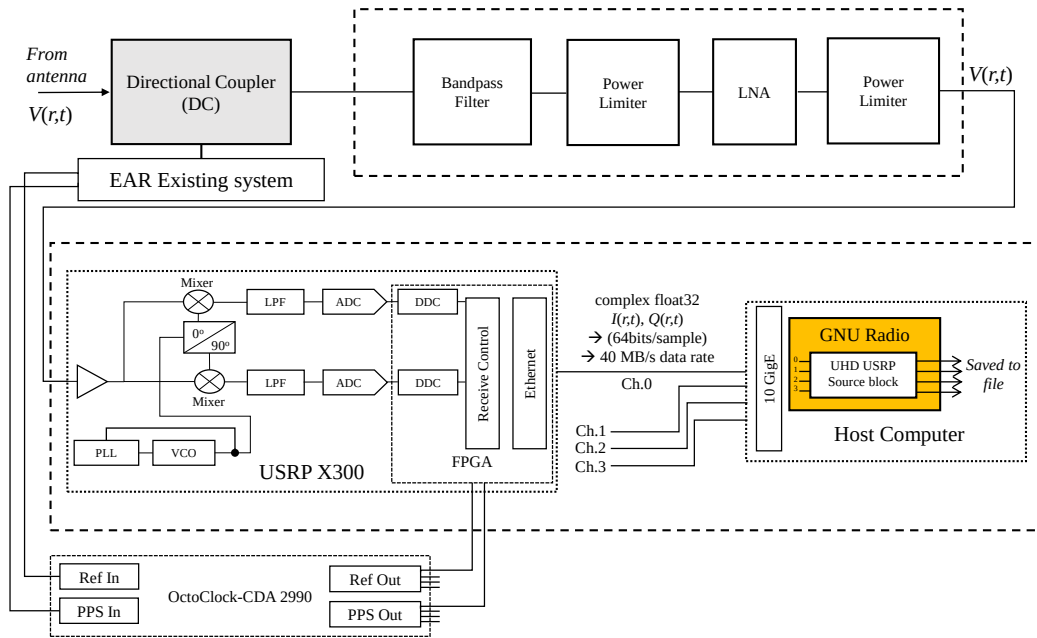


FIGURE 3.9: Block diagram of the software defined receiver.

3.3.1 Directional coupler

For utilizing the SA method, the EAR was divided into three receiving antennas consisting of a combination of subarrays 6 and 7 (Channel 1), 10 and 11 (Channel 2), and 22 and 23 (Channel 3) (see Fig. 1.4). Three receiving antennas, forming a triangle-shaped receiving system, enabled the SA method to be carried out while the transmission procedure was retained. The x -axis and y -axis shown in Figure 3.7 represent the axes where wind velocity components of the SA method were computed (see explanation below). Signals from each pair were combined and then split (or distributed) by a directional coupler to the newly-installed receiver through the coupled input (CPL-IN) port and to the existing receiving system of the EAR through the output (OUT) port, which was kept for the measurement of standard EAR observations. The newly-installed receiver comprised of an amplifier, a power limiter, anti-aliasing band pass filter and USRP X300 as the receiver. The power limiter ensures that the receiver will not be saturated due to the leaked transmitting pulse. The signals were then digitized with a sample rate of 5 Mega samples per second. The time series of IQ signals from the USRP X300 that were produced with a format of complex float32 were transferred to the PC through a 10 gigabit ethernet port. The specifications of the test observations are summarized in Table 3.2.

TABLE 3.2: Specifications of the test observation system

Item	Specification
Center frequency, f	47 MHz
Number of beams (n_{beam})	5
Inter pulse period (ipp)	400 μ s
Number of subpulse	16
Subpulse width	1 μ s
Pulse compression code	Spano's optimized*
Number of coherent integrations (n_{coh})	64
Number of data points (n_{data})	128
Number of range gates	128

*Spano and Ghebrebrhan [3]

3.4 Processing of the Signal

For the current development, the test observation data were stored directly on the HDD after being transferred from the USRP X300 to the PC. No switch-like mechanism was being employed in the software-defined multichannel (SDM) receiver, so the received echoes, including the transmitted pulse leaked to the receiver, were recorded. Therefore, the signal processing for radar functionality, e.g., ranging, pulse decoding etc., are conducted off-line. The data were required to go through several processing steps (Fig. 3.10) before the data are further analyzed for wind estimation. The Python programming language with the combination of Numpy, Scipy, and Matplotlib was utilized for signal processing because of its simplicity and readability. The initial step was to find the first transmitted pulse of the received signals. Cross correlation between the first Spano's code and the received signal is carried out in this step, where the 32 sequences of pulse compression code is known. This step determine the data timing for the rest of the data within a recorded observation period, and was carried out even after a no-transmission period of approximately 2 to 3 s.

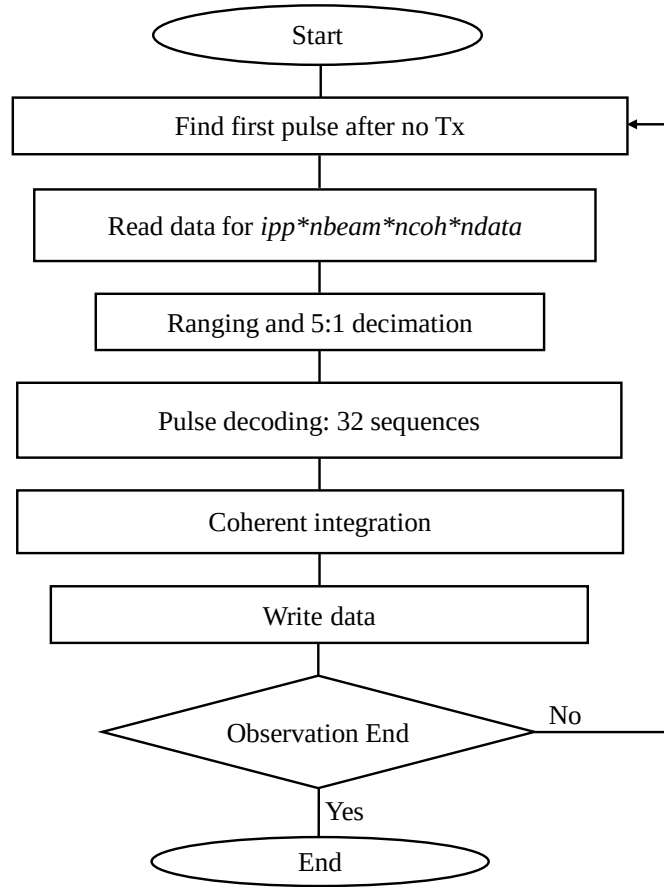


FIGURE 3.10: Flow chart of the signal processing.

A single data reading corresponds to a total period of 16.384 s. A complete loop consists of ranging, pulse decoding from 32 code sequences, coherent integration up to 64 times, and data writing. For a complete cycle of pulse transmission consists of five beams (vertical, north, east, south and west direction), the same code is used, and then the next code in the sequence is assign to the subsequent cycle. The data reading is continued until the end of the observation data. A predetermined threshold, which uses transmitted pulses leaked to the receiver as a trigger marks the start of the ranging process. This is due to its exceedingly high amplitude compared to the received echoes that are much smaller in amplitude. The concept is illustrated in Figure 3.11. A similar method was utilized by Yamamoto et al. [58] for range sampling of a 1.3 GHz wind profiler radar. Once the ranging is started, the data will be sorted in the range direction until it reaches the maximum range gate, and continued for the next pulses consecutively before pulse demodulation is applied.

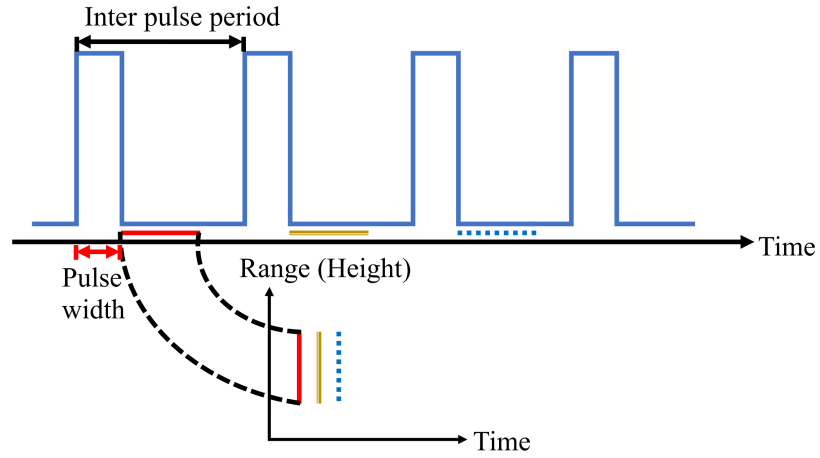


FIGURE 3.11: Concept of the range sampling.

The sample of leaked transmitted pulses detected by the receiver is shown in Figure 3.12 where the top, middle, and bottom figures are the squared magnitudes of the IQ signal, the I (solid line) and Q (dashed line) signal, and its phase, respectively. The sample lasts for $16 \mu\text{s}$, which corresponds to the pulse width of the transmitted signal. From Figure 3.12 (refer to the top figure), we could confidently set a magnitude of 0.12 as a threshold to detect the leaked pulse.

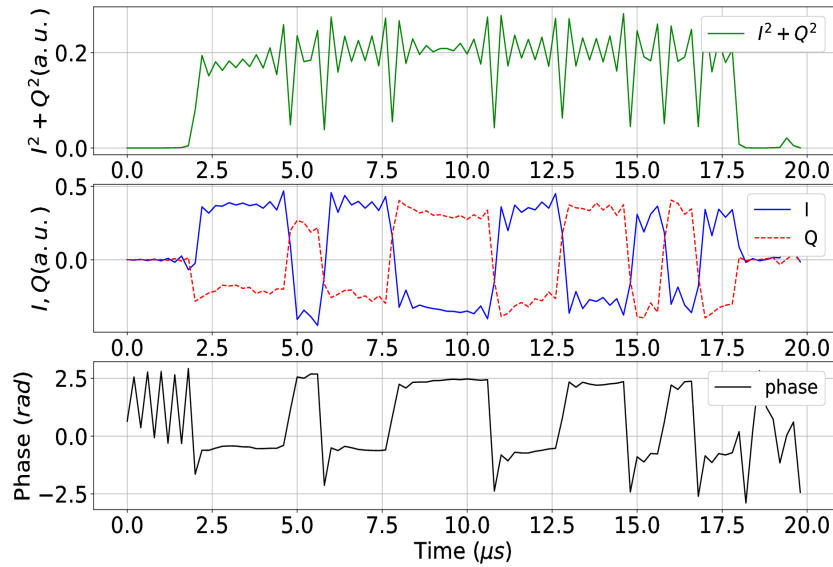


FIGURE 3.12: Sample of the pulse leaked to the receiver.

The demodulated data were then coherently integrated to reduce the amount of data as well as to improve the signal to noise ratio (SNR). The data were then saved in .npz

format output files to be used for further analysis. For ease of access later, the .npz files were labeled according to their channel's origin and the number of loops that occurred. The size of each file was significantly reduced to make the offline processing easier. Figure 3.13 illustrates the samples of data from the .npz file that were transformed using fast Fourier transform (FFT) from each channel. It shows the Doppler velocity versus range for five different beam directions.

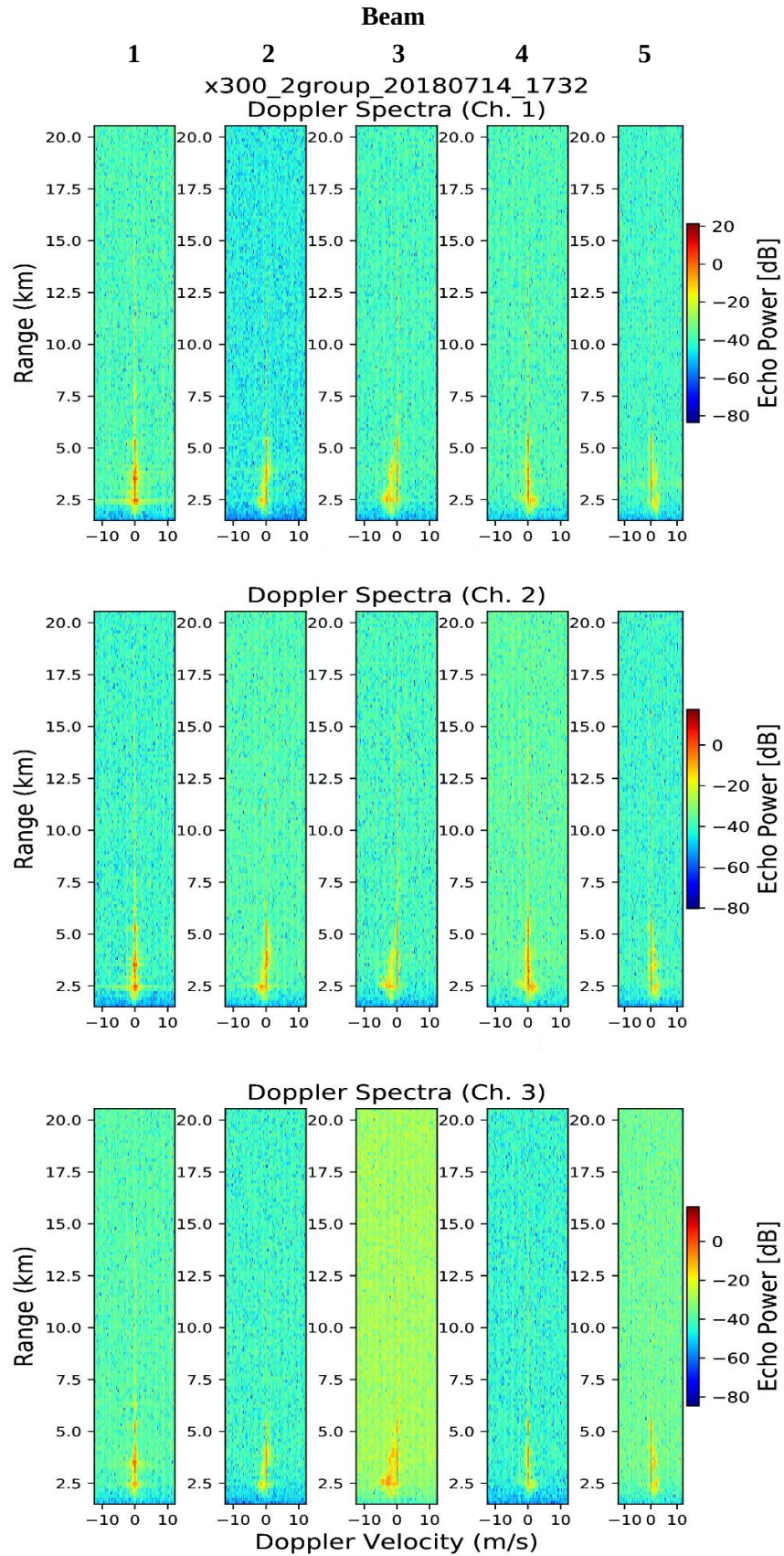


FIGURE 3.13: Sample of Doppler spectra from channel 1 (top), channel 2 (middle) and channel 3 (bottom). Beam 1 is vertical beam, while beams 2, 3, 4, and 5 are oblique beams, 10° from zenith at azimuth angle of 0° , 90° , 180° , and 270° respectively.

3.5 Full Correlation Analysis

After the data were saved in the .npz format, they were used as input for full correlation analysis (FCA) for determining the wind field vertical profile used in the spaced-antenna method. It was developed by Briggs [59] for retrieving wind velocity and other information from correlation functions. The principle and equations regarding the method are found in Briggs [59] and Hocking et al. [1], and are included in Appendix A.

Under the FCA method, the correlation functions take a form of Gaussian distribution function normalized to unity at zero lag. A sample of correlation function from the EAR multi-channel receiver's data is shown in Figure 3.14.

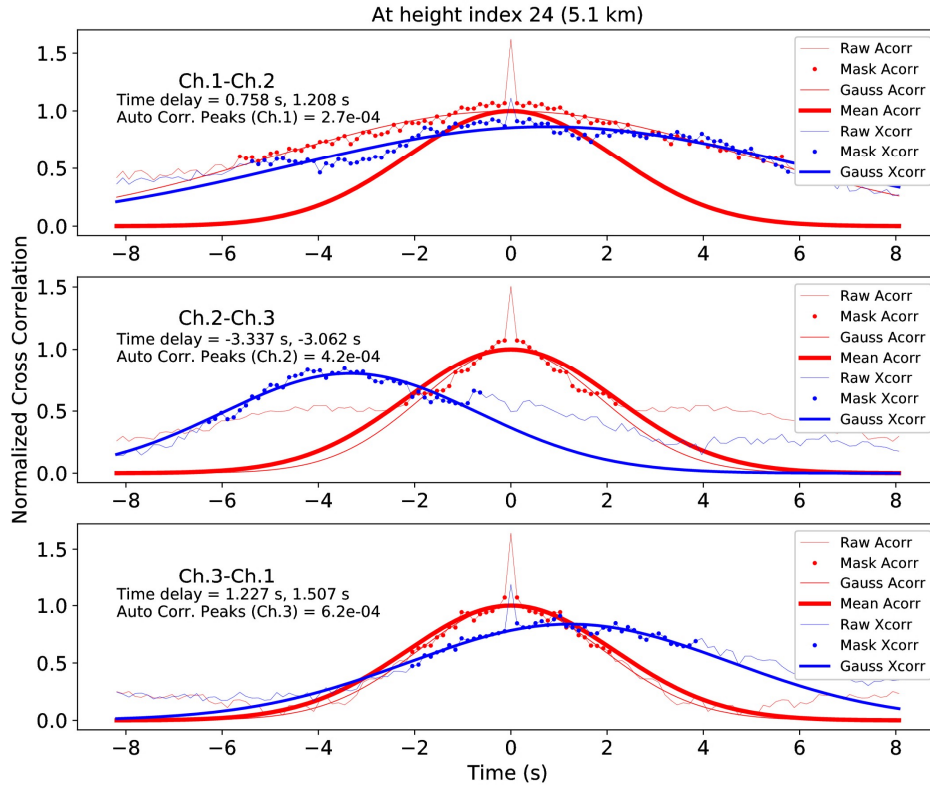


FIGURE 3.14: Sample of correlation function from the observation data using EAR multi-channel receiver.

Figure 3.14 approximately depicts the process of extracting the FCA parameter from a single .npz file. The initial correlation between channels (thin lines) produced a non-Gaussian distribution and therefore needed to be approximated to a Gaussian function as in the original method. Data rejection criteria is added before the fitting process

through masked dataset (labelled as Mask Acorr and Mask Xcorr for autocorrelation and cross-correlation respectively) to ensure the reliability of the least square fit. The Gaussian approximation (thick lines) of the autocorrelation and cross-correlation function is expressed as:

$$f(x) = P \exp \left(-\frac{(x - \mu)^2}{2\sigma^2} \right) \quad (3.4)$$

where P is the peak value (i.e., equal to one for autocorrelation), μ is the mean and σ is the standard deviation of the correlation data after the least square method was performed. The mean autocorrelation (thickest red line) was evaluated across the three channels.

The parameters obtained were then used to estimate the true velocity components using the following equations [59]:

$$AV_x + HV_y = -F \quad (3.5)$$

$$HV_x + BV_y = -G \quad (3.6)$$

where A , B , F , G , and H are the coefficients introduced in the FCA method, V_x and V_y are true velocity vector in x - and y -direction respectively (see Appendix A). The actual wind velocity vector, v_h comprises of zonal and meridional wind velocity, are related to V_x and V_y as follow:

$$\vec{v}_h = \begin{pmatrix} v_{zonal} \\ v_{meridional} \end{pmatrix} \quad (3.7)$$

$$V_x = 2\vec{u}_x \cdot \vec{v}_h \quad (3.8)$$

$$V_y = 2\vec{u}_y \cdot \vec{v}_h \quad (3.9)$$

where $\vec{u}_x$ and $\vec{u}_y$ are unit vector of x - and y -direction.

3.6 Observation Results

We evaluated the current results obtained from the EAR SDM receiver by comparing with the EAR standard observation. During the three test observations that were carried out, the height profile of the wind velocity vector were observed to consistently reach about 8 km. After the first test, some modifications were applied to the SDM receiver system such as replacing the high gain amplifiers with low noise amplifiers and varying the positions and number of amplifiers. The aim was to improve the SNR and therefore increase the observable maximum height. The results of the comparison on July 14, 2018 between the EAR SDM receiver and the EAR standard observation are shown in Figure 3.15.

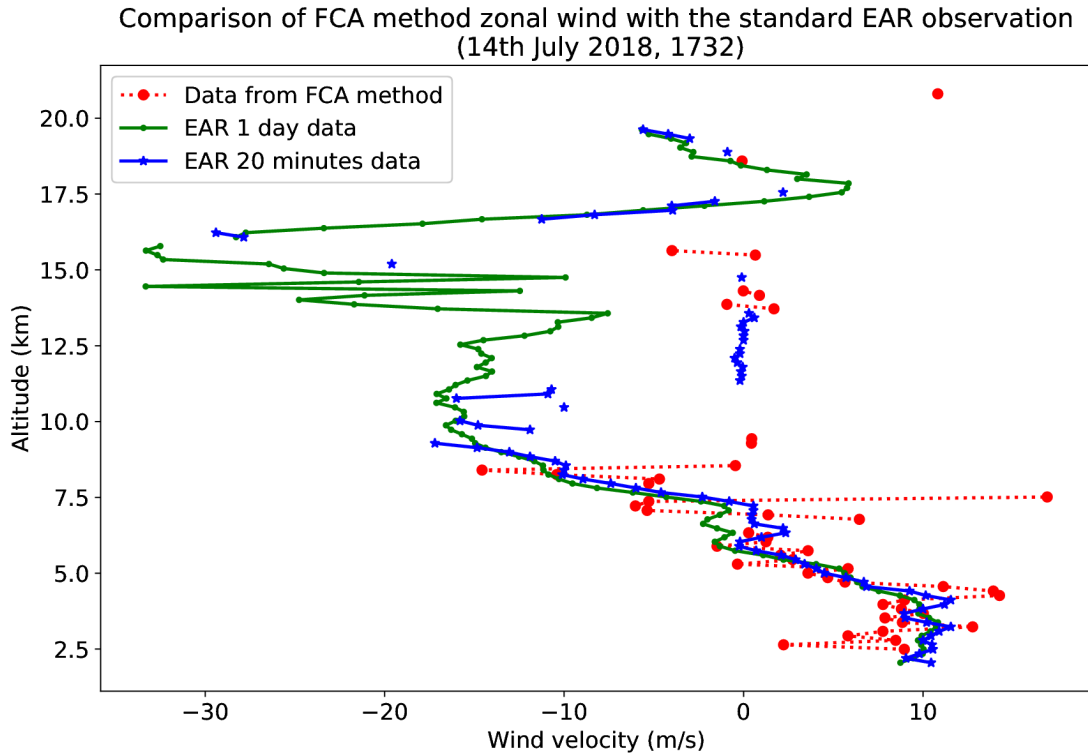


FIGURE 3.15: Comparison of zonal wind obtained from FCA analysis and EAR standard observation.

Figure 3.15 indicates that the observation patterns between the two systems were in concordance, although a noticeable fluctuation existed from the SDM receiver. Due to the fact that EAR standard observations are considered one of the established atmospheric radars, we could safely assume that the performance of the EAR SDM receiver is

reliable up to about 8 km observation height. It is notable that the EAR SDM receiver used data from a single beam (vertical beam) compared to the standard observation that uses five beams.

3.7 Summary

The current performance of the EAR multi-channel receivers is summarized. First, the aperture size of each receiving antenna is roughly one twelfth of the whole EAR, which consequently affect the receiver sensitivity. One of the main issue to be mitigated in the subsequent work is to improve SNR (i.e., increasing the aperture size of the receiving antennas). Second, the separation distance between each receiving antennas might lead to weak correlation between channels. This condition could be one of the factor that causes high fluctuation from the SDM receiver-estimated zonal wind as in Figure 3.15. Third, up to the current results, the correlation for FCA is performed on the data that incoherently integrated once. Increasing the number of incoherent integration could probably improve the SDM receiver performance in the expense of longer temporal resolution. Subsequent works (Chapter 4) is conducted by taking into consideration all mentioned factors to improve the current EAR SDM receiver to include real-time signal processing and improve the maximum observable height.

Chapter 4

Analysis of Spaced-Antenna Performance on EAR Multichannel Receiver System

4.1 Introduction

Based on the previous chapter, there were limitations shown by the observations from the multichannel receiver. Initial configuration used two antenna groups for each receiving channel, and the separation distance between each receiver was approximately 58 m and 54 m apart for x -axis and y -axis respectively. Furthermore, the size of each receiver was considered small (one twelfth of the EAR) though, in SA method, such configuration is expected, as it took advantage of the strong echo from partial reflection.

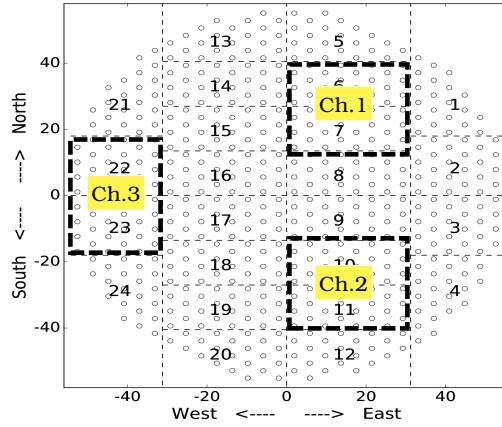
However, the existence of the fluctuation in the estimated wind was noticeable, therefore, a few modifications to the configuration of the SA receivers are required. To that aim, we included four additional configurations considering the aperture size of the receivers and their separation distance, and compare the outcome with the initial configuration. We also estimated horizontal winds using FCA method from all configurations, and compared with EAR standard observation data, and then, the linear regression analysis are performed on the resulted data.

4.2 Experimental Setup

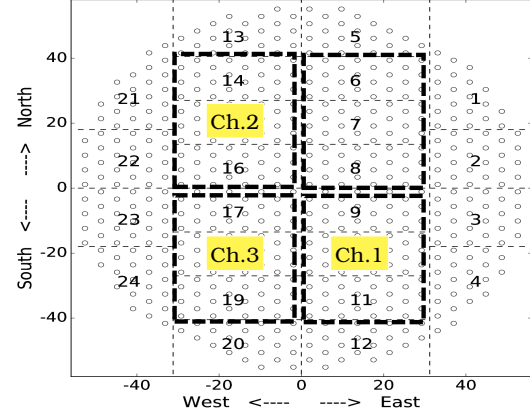
Most works associated with SA method are achieved using three non-collinear receiving antennas which usually form the equilateral triangle pattern. However, we could not use the equilateral triangle for testing the SA method on EAR due to its pattern and also limitations in terms of the number of channels currently available. However, we believe that such limitations should not produce any significant issue since the original FCA method derived by Briggs [59] allows for non-equilateral patterns of the receiving antennas as long as all the receiving antennas are non-collinear. Figure 4.1 shows an illustration of the five configurations that were tested using the developed multichannel receiver. The configuration is summarized as in Table 4.1 showing the antenna groups that are being utilized to form a different orientation for applying spaced-antenna method and its respective channel number.

Test observations have been conducted between April 2019 and September 2019 for testing the performance and the difference between all configurations of the EAR SA method. The first test was conducted between April 25 and April 28, 2019, the second test was conducted between August 22 and August 24, 2019 and the third test was conducted between September 25 and September 28, 2019. Testing for configurations 4 and 5 is added during the second and the third test respectively. Note that diurnal variation is not considered in the testing. Therefore, the duration of the test includes day and night without any fixed restriction to the observation.

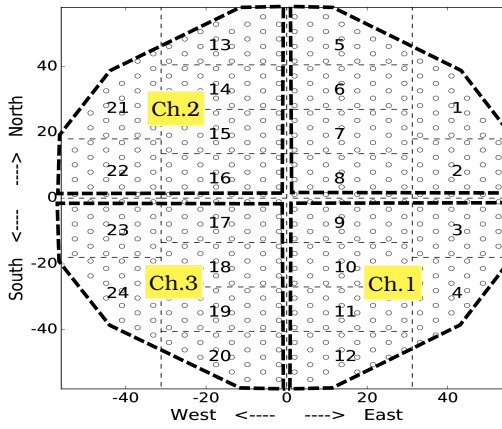
Based on Figure 4.1, all orientations established non-equilateral triangle by considering the center of the receiving antennas as a receiving point. In configurations 1, 4, and 5, the channels 1, 2, and 3 receive signals collected by the assigned antenna groups and channel 0 is used for collecting signal from the whole antenna. Configurations 2 and 3 utilized all assigned antenna groups to received signal which will be utilized for different analysis which is not covered by the scope of this paper. It is worth mentioning that only signal from channels 1, 2, and 3 will be used which is sufficient for estimating horizontal wind using FCA technique, while channel 0 is not considered.



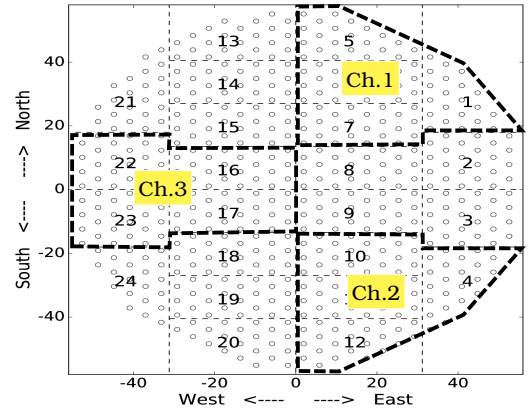
(A) Configuration 1



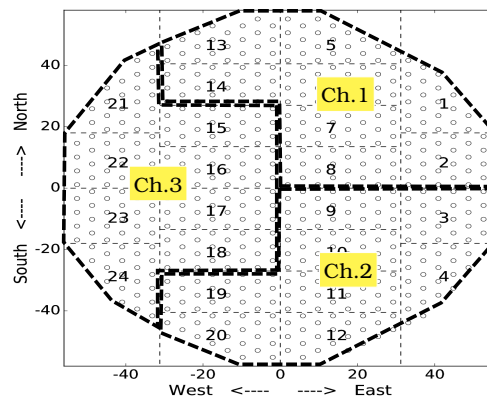
(B) Configuration 2



(C) Configuration 3



(D) Configuration 4



(E) Configuration 5

FIGURE 4.1: Multiple configurations for the EAR SA method experiment

TABLE 4.1: Summary of the EAR SA multi orientation

Configuration	Antenna groups	Channel mapping
Conf. 1	(All), (6,7), (10,11), (22,23)	Ch.0, Ch.1, Ch.2, Ch.3
Conf. 2	(6,7,8), (9,10,11), (14,15,16), (17,18,19)	Ch.0, Ch.1, Ch.2, Ch.3
Conf. 3	(1,2,5,6,7,8), (3,4,9,10,11,12), (13,14,15,16,21,22), (17,18,19,20,23,24)	Ch.0, Ch.1, Ch.2, Ch.3
Conf. 4	(All), (1,5,6,7), (4,10,11,12), (16,17,22,23)	Ch.0, Ch.1, Ch.2, Ch.3
Conf. 5	(All), (1,2,5,6,7,8,13,14), (3,4,9,10,11,12,19,20), (15,16,17,18,21,22,23,24)	Ch.0, Ch.1, Ch.2, Ch.3

4.3 Real-Time Signal Processing and Data Analysis

The recorded data in the previous work requires a large hard disk drive (HDD) space to be stored for post processing [60]. Therefore, to overcome such a limitation, a software system that combines SDR data acquisition and the atmospheric radar signal processing is developed. The flow of the processing is mostly retained as in the previous chapter and ranging, pulse-decoding and coherent integration are conducted. Finally, the data at each height range are stored as binary information. This step significantly reduces the size of the stored data (approximately 1/1000) and more observation data are available for further analysis. However, there is an additional procedure (i.e. phase correction) in the real-time signal processing to overcome the slight imperfection in the synchronization of the multiple X300 channels.

As deliberated in Section 3.2.6, there is slight phase difference existed between all channels, on the same board and across different board, because there is no internal mechanism to perform phase alignment. Therefore, an external mechanism has to be implemented for phase correction across all channels. As the leakage of the transmitted signal is received by all channels, we could use it to improve the synchronization accuracy between channels, in which variation of the phase is corrected, so that the phase of the transmitted wave received at X300 is the same for all channels and all transmitted pulses. If the signal from EAR is expressed as:

$$V_{EAR}(r, t) = A_E \cos \left(2\pi f_{0EAR}t - \frac{4\pi r}{\lambda} + \varphi_0 \right) \quad (4.1)$$

and the local oscillator signal from USRP is expressed as:

$$V_{USRP}(t) = A_U \cos (2\pi f_{0USRP}t) \quad (4.2)$$

after the signals are mixed, and by removing the high frequency component, the expression becomes:

$$V(r, t) = A \cos \left(2\pi (f_{0EAR} - f_{0USRP})t - \frac{4\pi r}{\lambda} + \varphi_0 \right) \quad (4.3)$$

If the frequency difference, $\Delta f = f_{0EAR} - f_{0USRP}$ can be determined, the phase of the received signal can be corrected as well. The phase difference is in the order of 10^0 Hz.

Two programs (data acquisition and radar signal processing) are running on a LINUX system. The flow of the phase correction for one spectrum is shown in Figure 4.2. 1 GB shared memory (time to fill the buffer is $1 \text{ GB} / (8 \text{ B} * 5 \text{ M/s}) = 25 \text{ s}$) is allocated to each channel (i.e. banks 0, 1, 2, and 3) for the implementation of real time signal processing. After the signal is received by real-time signal processing, the transmitted pulse is judged using *skip_tx()* (refer to Appendix B) function where a value of five times the maximum value of the non-transmission pulse is set as a threshold. Then, the head of the code sequence is specified by correlating the received signal with the sequence of Spano code [3]. In the first loop, pulse adjustment and ranging is carried out before decimation for reducing the size of data. In the second loop, each channel is synchronized in units of $0.2 \mu\text{s}$ using a pulse code. The phase is then corrected by assuming that the phase drift is linear within the coherent integration time (128 ms). After that, the corrected data is written to file for post processing and all the process is repeated until the end of observation data.

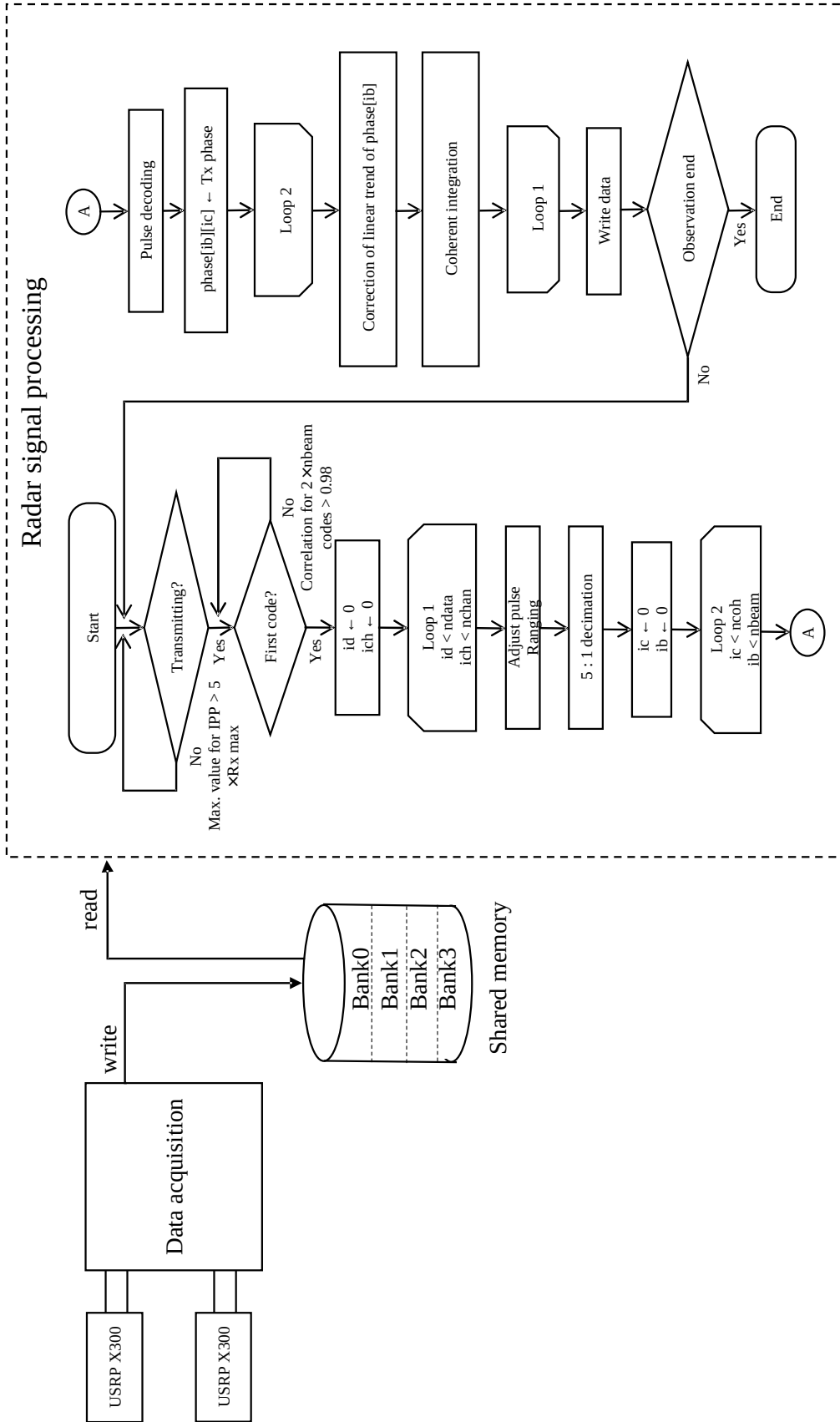


FIGURE 4.2: Flow of the phase correction for a single spectrum in real time processing.

4.4 Experimental Observation Results

In this section, a few comparison results from the observation samples are presented. We compared the Doppler spectra and horizontal wind (i.e., zonal and meridional) and, using the standard EAR data as benchmark, analyzed the performance of the FCA-estimated horizontal wind through regression analysis.

4.4.1 Doppler spectra comparison

Figures 4.3 – 4.7 show the sample of Doppler spectra after 25 times incoherent integration for configurations 1 – 5, respectively. For configuration 1 (Figure 4.3), it was observed that the maximum height observable could reach approximately 10 km height, based on channels 0, 1, and 3. The spectra from channel 2, however, shows much lower observable height. However, it was too early to assume that an unknown technical issue has arisen because it might also be assumed to be due to weak return echoes, which specifically observed by the mentioned receiving channel.

If we observe the results in configurations 4 and 5 (Figures 4.6 and 4.7), the Doppler spectra from channel 2 turn out better, if compared to the sample from configuration 1. This results show that there was no technical issue concerning the receiving channels. However, any type of atmospheric phenomenon is as an assumption, and will not be further discussed as in the scope of this study.

The sample of Doppler spectra from configuration 2 (Figure 4.4) shows that the observable height reaches approximately 7.5 km altitude. In comparison, configuration 3 (Figure 4.5) shows slightly higher observable height, which could be due to larger aperture size of the receiving antennas. From the Doppler spectra of all configurations, we are able to deduce that the height profile that could be observed using the EAR multichannel receiver is sufficient for 10 km height coverage. Such information, although still do not consider for long term observation, should give us an insight regarding the performance of the current EAR multichannel system.

One of the key points that worth mentioning is, spectra from channel 0 (produced from the whole EAR antenna as receiver) does not show any significant improvement compared to channels 1, 2, and 3 in term of the maximum observable height. Almost

a similar pattern could be observed from the configurations 1, 4, and 5 (Figures 4.3, 4.6, and 4.7 respectively), where channel 0 only shows improvement in the background noise/clutter (notice the horizontal noise along the centre of the spectra). This behavior is important to be noted, because the difference in the aperture size between channel 0, and channels 1, 2, and 3 (from configurations 1, 4, and 5), is quite significant. In fact, we presumed that, at least a small improvement in the observable height for all the three cases on channel 0 (configurations 1, 4, and 5) should be observed, however, it did not turn out as expected. Therefore, from the findings, we concluded that the limit of our multichannel receiver was at its maximum capability up to about 10 km, in terms of SNR.

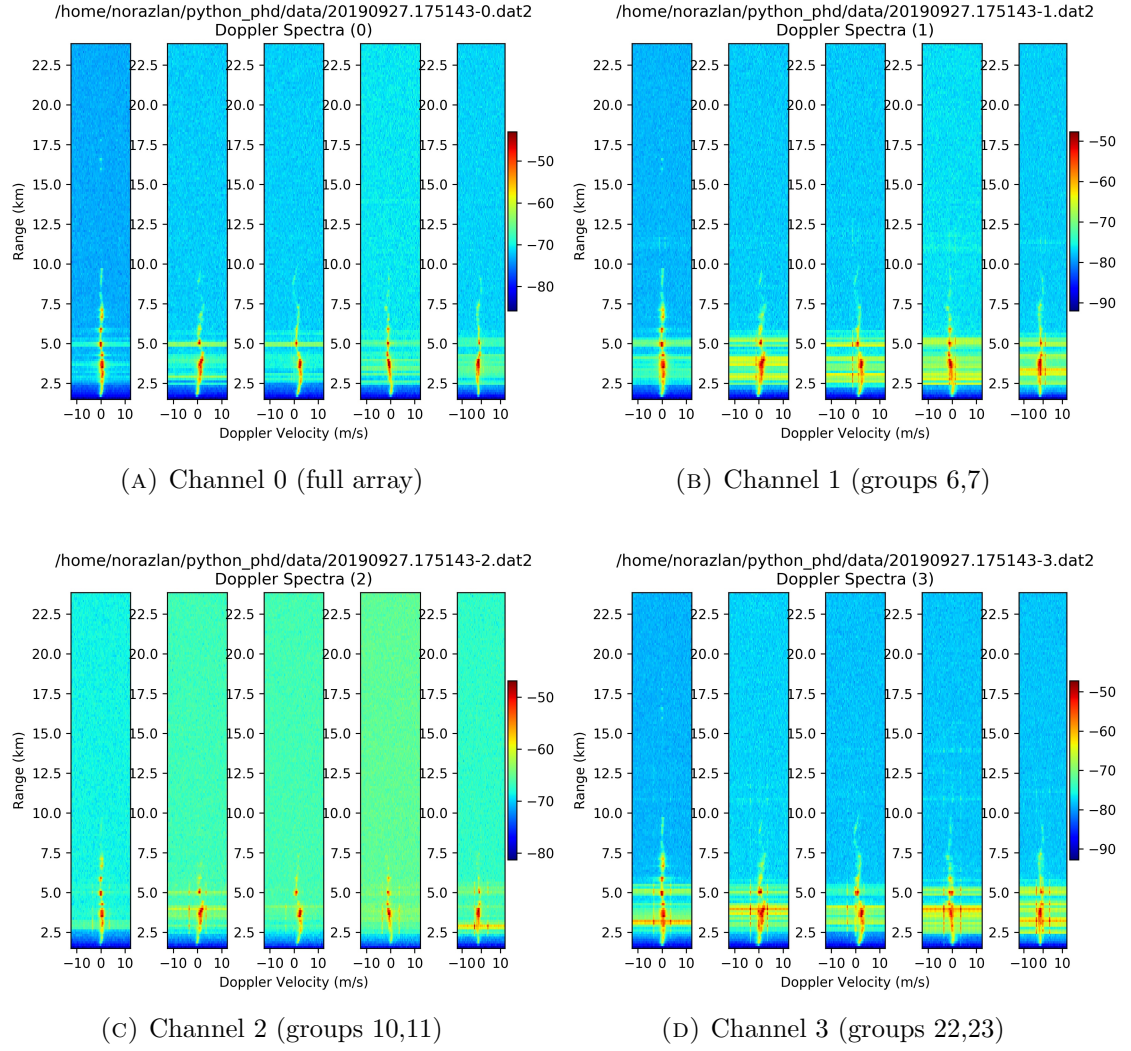


FIGURE 4.3: Sample of Doppler spectra from configuration 1

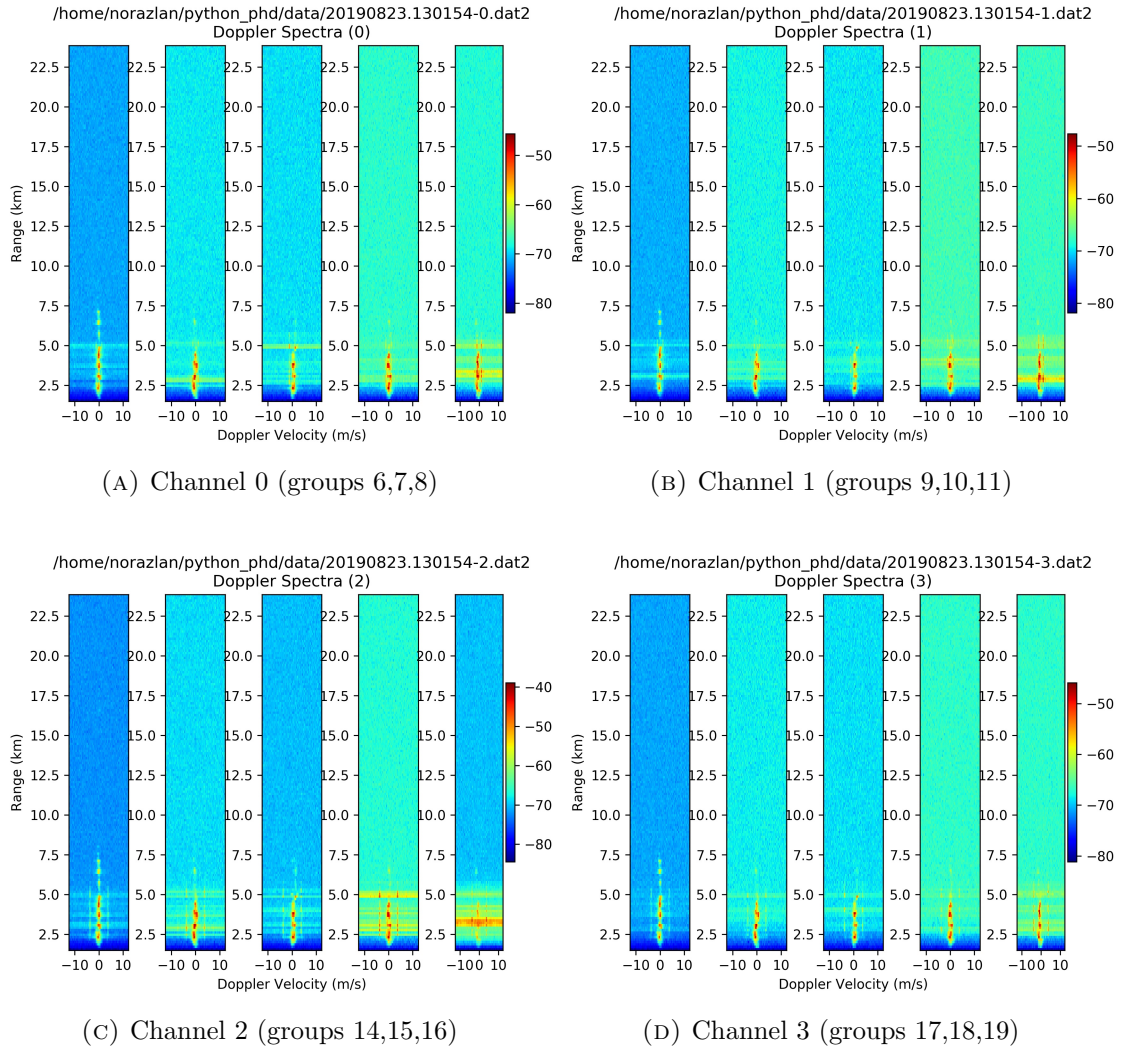


FIGURE 4.4: Sample of Doppler spectra from configuration 2

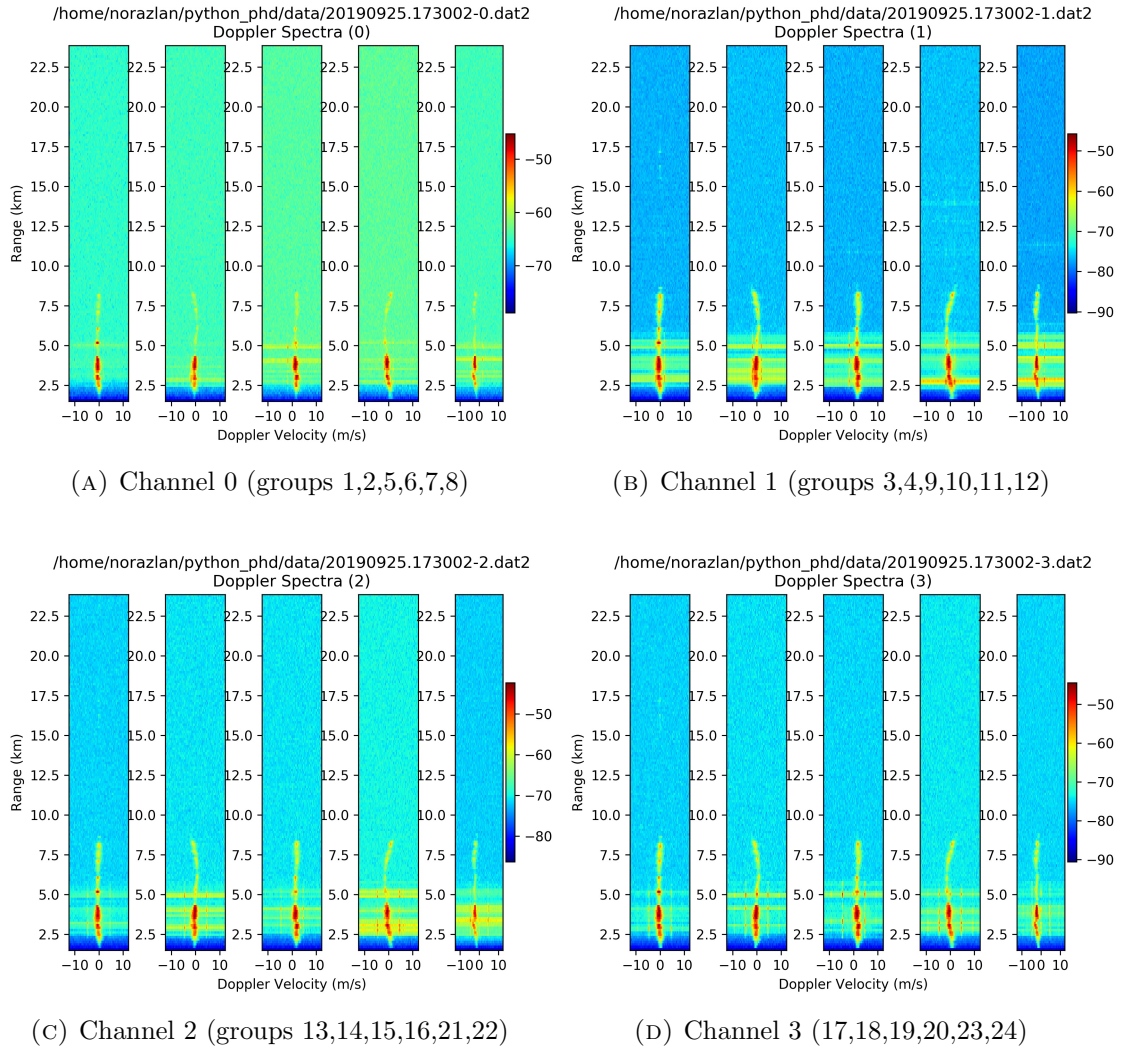


FIGURE 4.5: Sample of Doppler spectra from configuration 3

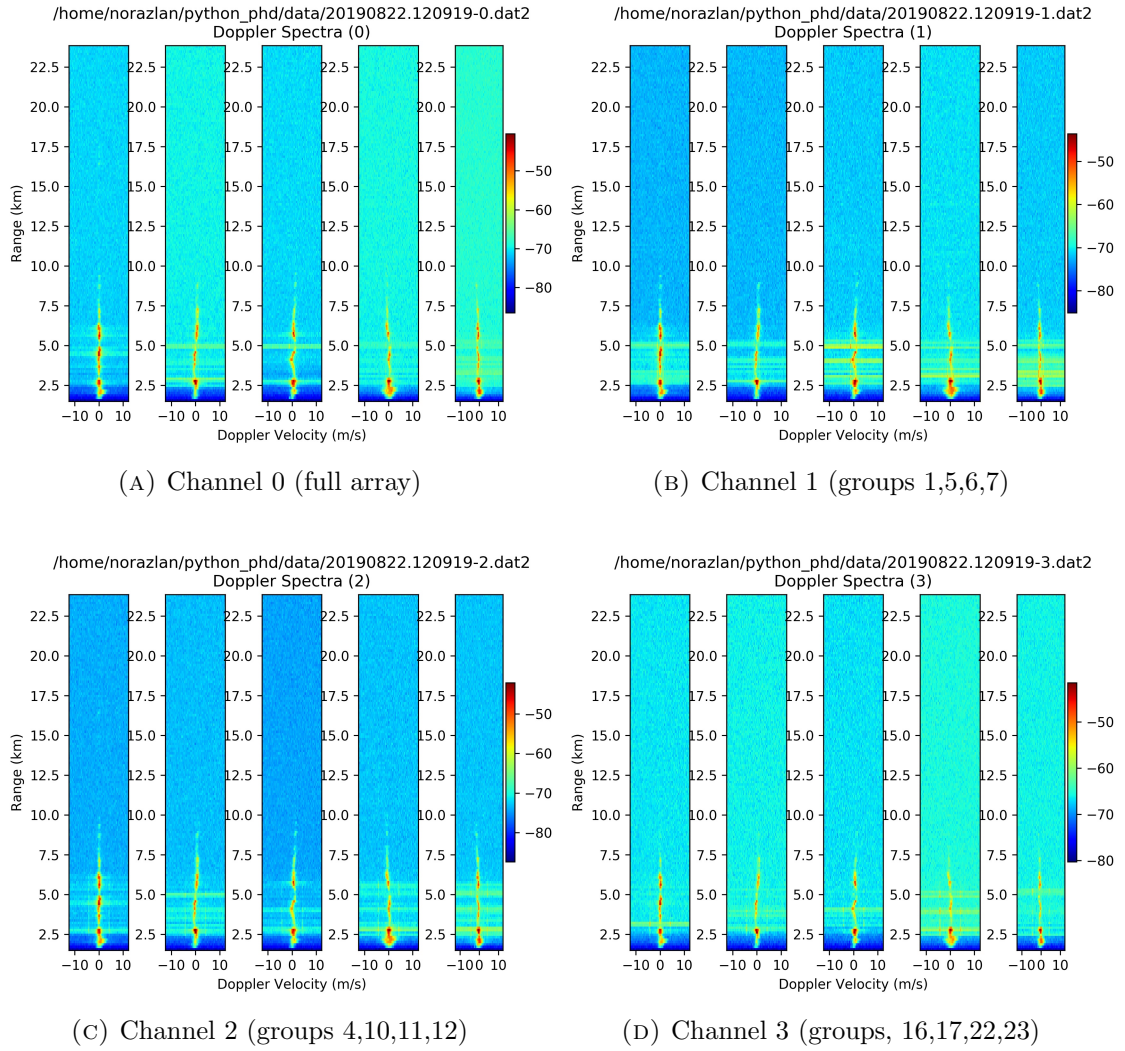


FIGURE 4.6: Sample of Doppler spectra from configuration 4

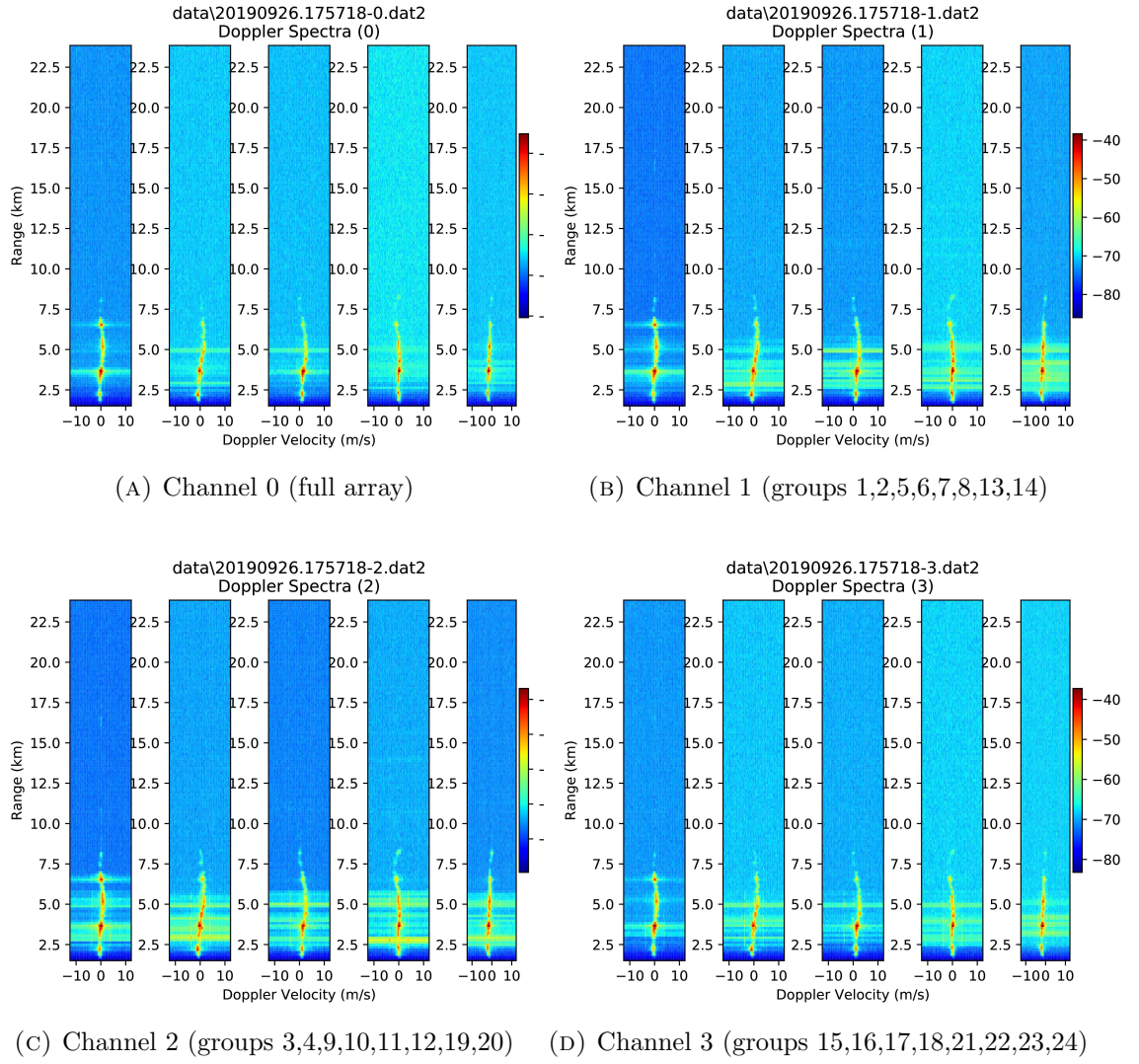


FIGURE 4.7: Sample of Doppler spectra from configuration 5

4.4.2 Horizontal wind comparison

Although brief understanding on the performance of the current EAR multichannel receiver system is attainable from Doppler spectra, it is also worth to figure out how it performs when estimating horizontal wind profile using Full Correlation Analysis (FCA). Figure 4.8 shows the illustration for wind estimation using FCA for configurations 1, 4, and 5, and configurations 2 and 3 (left and right, respectively). Wind estimation for configurations 1, 4, and 5 are obtained using similar procedure as in the Chapter 3, while for configurations 2 and 3, the procedure has been slightly modified.

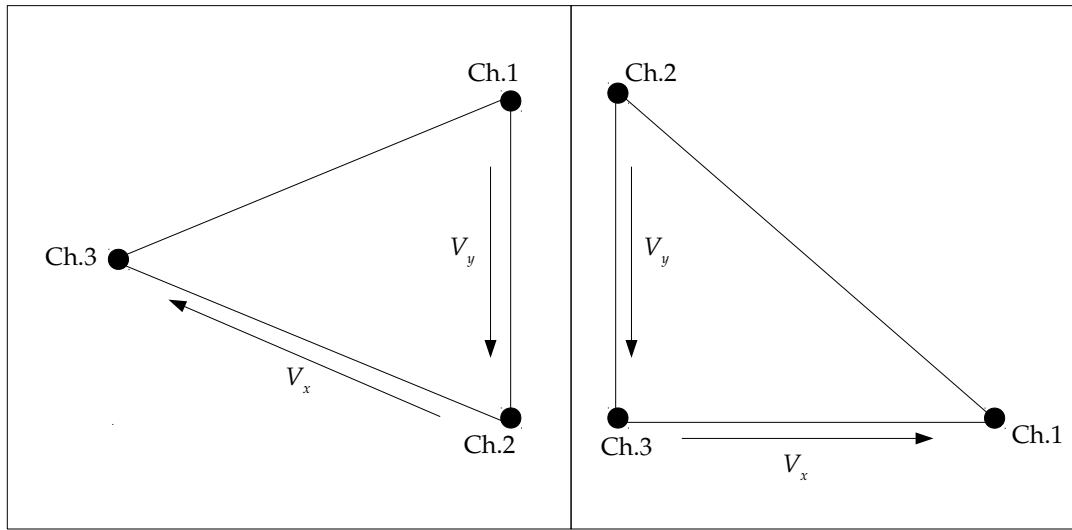


FIGURE 4.8: Illustrations of FCA procedure for configurations 1, 4, and 5 (left) and configurations 2 and 3 (right).

Figures 4.9 – 4.13 show the comparisons of zonal wind and meridional wind from FCA estimation and EAR standard data. The comparisons are carried out using the average of a few hours data from FCA method and approximately the same period from the average of EAR standard data. The data from FCA has also been filtered out to remove any unwanted data which is more than 40 m/s for zonal wind, and 30 m/s for meridional wind. In both cases, there is no specific justification for the filtering threshold value, but it was an approximate value to roughly represents a practically relevant horizontal wind velocity. For configuration 1, zonal wind and meridional wind seems to agree well with the standard EAR data. However, the pattern similarity could be observed up to about 7.5 km to 8 km height only. Beyond that, fluctuations seems to be larger. There are data points from 10 km and above that seems to be obtained at 0 m/s velocity, that show agreement with EAR standard data. Data in this range, however, might not be reliable.

Similar patterns are observed from configurations 2, 3, and 4. For configuration 2, it seems that the similarity could be observed up to about 7.5 km height, for both zonal and meridional wind. Again, we obtained a few data around 0 m/s velocity from 7.5 km and above for both zonal and meridional. Configuration 3, compared to configuration 2, shows better wind estimation as it reach up to about 10 km height. But, for zonal wind, the fluctuation is high, while it looks better for meridional wind. Configuration 4

also shows good wind estimation for meridional wind up to about 9 km. For zonal wind, although the pattern looks good, it also suffer due to large fluctuation.

Lastly, for configuration 5, the result seems a bit different than the other four configurations. In terms of agreement with the EAR standard data, it is considered good, however, in both zonal and meridional wind, there are slight underestimation in terms of wind velocity. It can also be observed from configuration 5 that the observation is good up to about 9 km to 10 km.

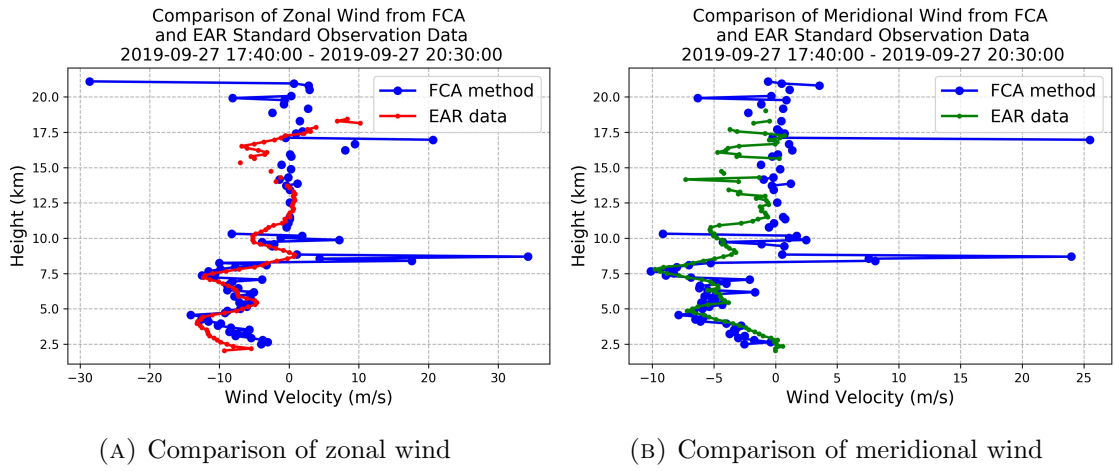


FIGURE 4.9: Comparison of zonal and meridional wind between FCA-estimated and EAR standard observation data from configuration 1

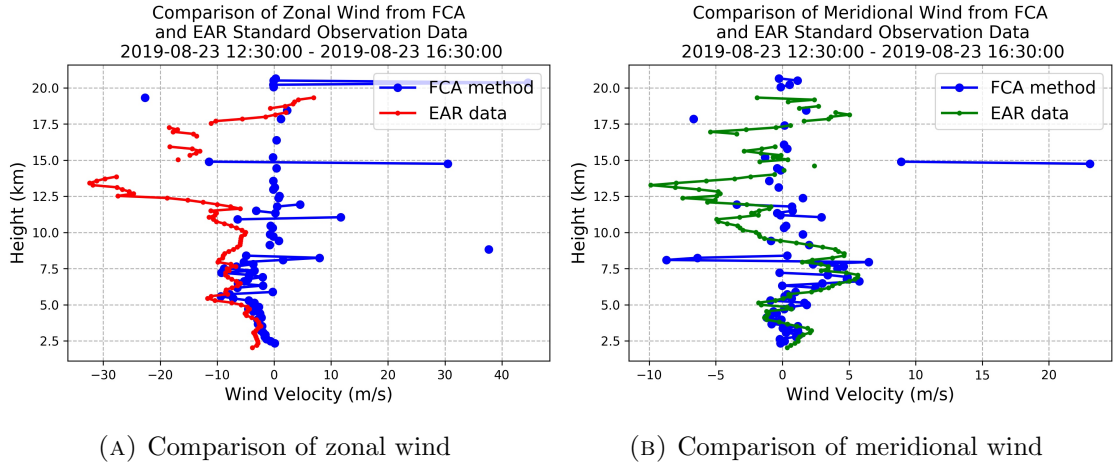


FIGURE 4.10: Comparison of zonal and meridional wind between FCA-estimated and EAR standard observation data from configuration 2

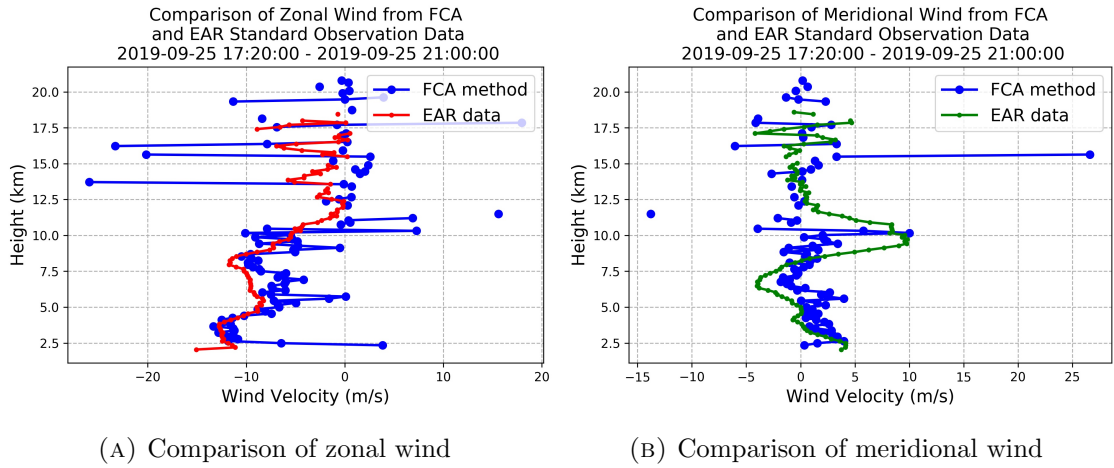


FIGURE 4.11: Comparison of zonal and meridional wind between FCA-estimated and EAR standard observation data from configuration 3

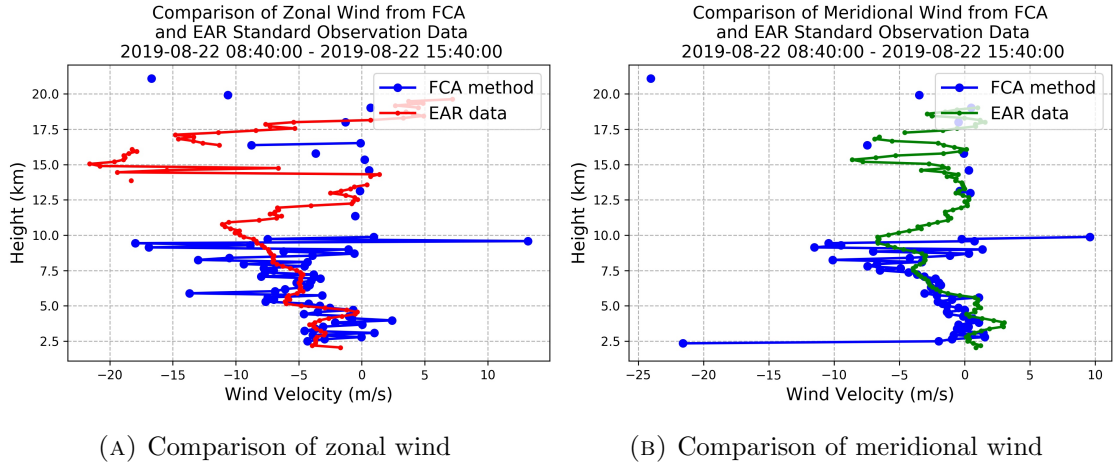


FIGURE 4.12: Comparison of zonal and meridional wind between FCA-estimated and EAR standard observation data from configuration 4

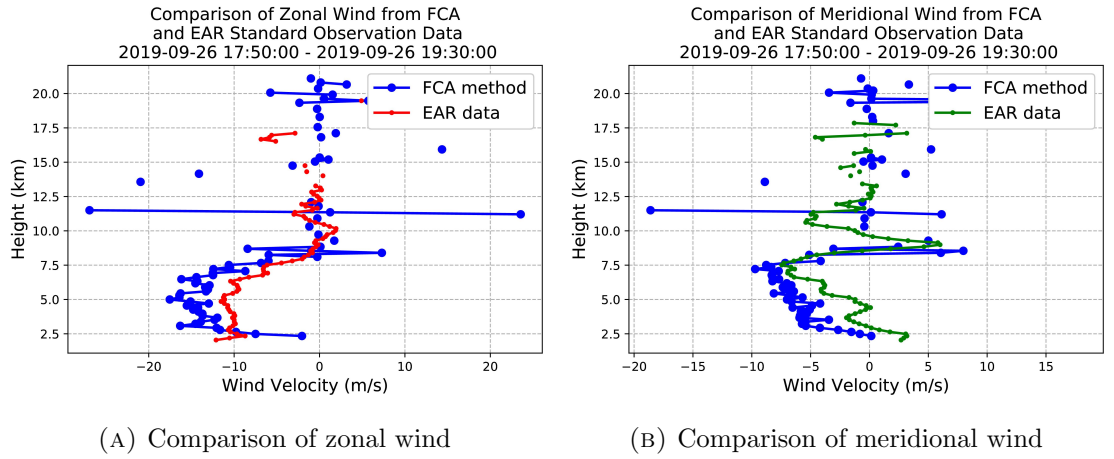


FIGURE 4.13: Comparison of zonal and meridional wind between FCA-estimated and EAR standard observation data from configuration 5

4.4.3 Linear regression analysis

To further analyze the results, ordinary least square (OLS) linear regression is carried out on sample of data collected from the experiments. Data rejection or filtering, similarly for estimating horizontal wind, is performed where values more than 40 m/s and 30 m/s for zonal and meridional wind, respectively, are removed before the averaging. Also, data between 2 km and 10 km are used in the regression to properly represent the regions where the received echo signal is detectable by our multichannel receiver. Figures 4.14 and 4.15 show the scatter plot of the horizontal wind from FCA-estimated and standard EAR with its respective correlation coefficient. The solid line is the line fitted to the data using OLS linear regression while the dotted line is the supposedly line of equality for x and y axes.

It is worth mentioning that, the EAR standard observation data are expected to produce less error in this case, because the standard data use all the five beams (vertical and four oblique with 10° zenith angle), steered on pulse-to-pulse basis but FCA-estimated use only vertical beam. Therefore, the OLS linear regression is suitable to represent the performance of the FCA-estimated horizontal wind where error is expected to be larger (based on previous work [60]). Both results from Figures 4.14 and 4.15 are produced by averaging more than 1-hour data. Similar analyses with 10-min data averaging are performed and summarized in Table 4.2.

From the results in Table 4.2, it is difficult to ascertain if the correlation coefficient is improving over longer periods of averaging as there is a situation where the correlation coefficient dropped from 10-min to 1-hour (e.g., configuration 1, 2, and 5 for zonal wind and configuration 1 and 3 for meridional wind). In terms of performance, though the results are obtained from sample experiments, there are few cases where almost no correlation was found between FCA-estimated and standard EAR. One of the assumptions that could be made with the set of obtained data currently is, atmospheric condition during the measurements will most likely influence the performance of the EAR multichannel receiver.

A few cases show quite outstanding performance such as 10-min averaged and more than 1-hour averaged (all data) from configuration 5. We may assume that such results are produced due to the occurrence of a stable layer in the atmosphere, which returns strong echo towards the receiving antenna, thus improving the SNR. Further, similar

assumptions could be proposed for few instances of bad data which might be due to the absence of a stable layer for specular reflection. Within the scope of analysis, configuration 5 performs well as compared to the other configurations. It is as expected especially due to the larger aperture size of its receiving antenna. However, based on the results, different approaches of signal acquisition and/or processing must be implemented before the signal arrives at the USRP X300 in order to achieve significant improvement in the overall performance of the EAR multichannel receiver.

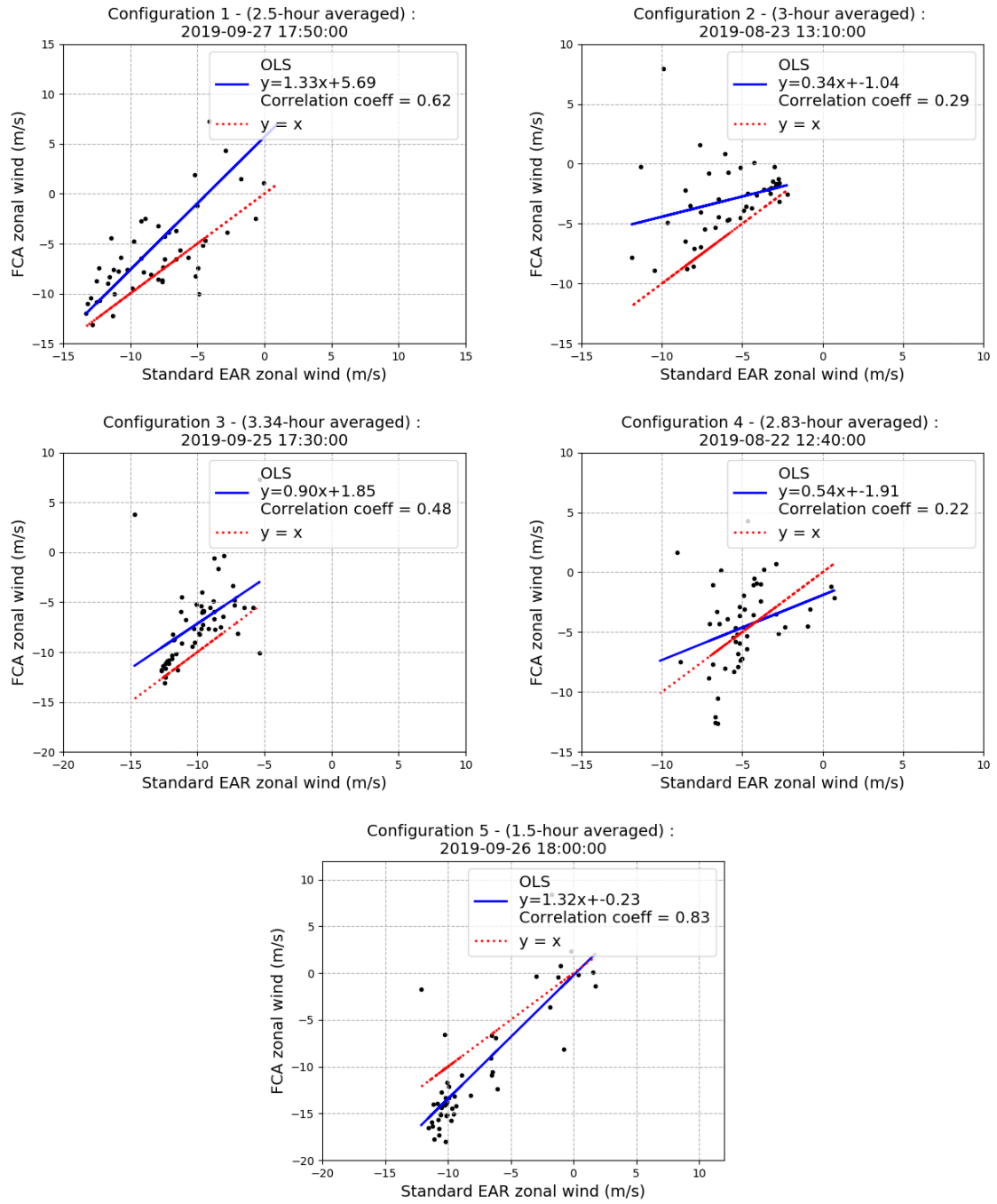


FIGURE 4.14: Comparison of linear regression on the zonal wind estimated from FCA and standard EAR data for all configurations.

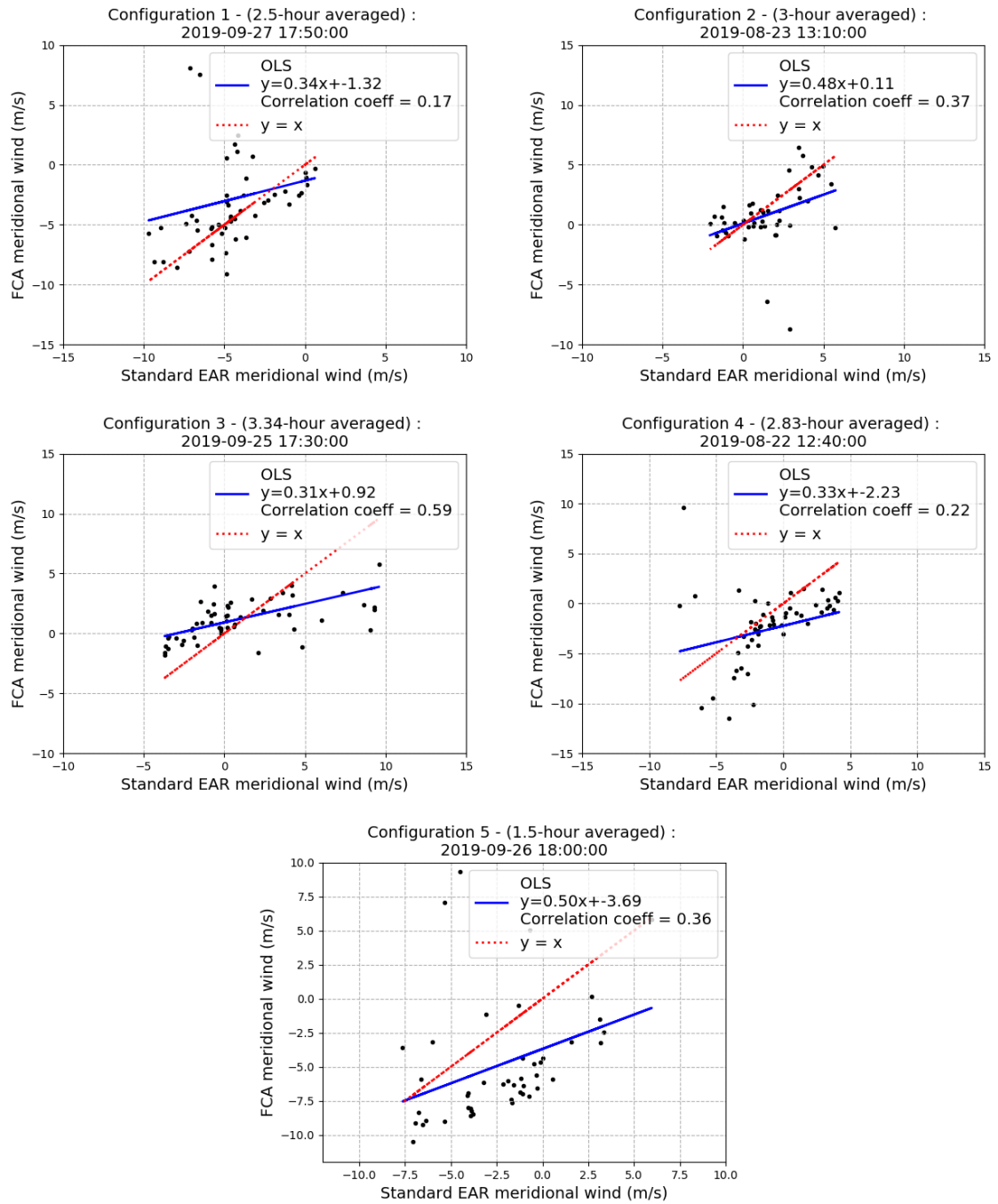


FIGURE 4.15: Comparison of linear regression on the meridional wind estimated from FCA and standard EAR data for all configurations.

TABLE 4.2: Correlation coefficients from linear regressions performed on FCA-estimated and standard EAR horizontal wind data.

	Correlation Coefficient							
	Zonal				Meridional			
	10-min averaged		All aver- aged		10-min averaged		All aver- aged	
Configuration	10- min	1- hour	> 1-hour	> 1-hour	10- min	1- hour	> 1-hour	> 1-hour
1	0.52	0.32	0.34	0.62	0.47	0.3	0.26	0.17
2	0.31	0.29	0.35	0.29	0.09	0.24	0.27	0.37
3	-0.08	0.03	0.11	0.48	0.29	0.04	0.10	0.59
4	0.02	0.29	NA	0.22	0.18	0.19	NA	0.22
5	0.78	0.55	0.55	0.83	0.04	0.34	0.26	0.36
Best conf.	5	5	5	5	1	5	2	3

4.5 Summary

Five configurations with different orientations of receiving antennas have been tested using newly installed EAR multichannel receiver system. The initial intention is to improve the maximum observable height, while simultaneously improving the estimation accuracy of the horizontal wind. Based on the results, it appears that the configuration 5 (Figure 4.1 (e)) shows a slight advantage over the other configurations and is sufficient for adopting the SA method on the EAR, but requires a different approach to the signal acquisition technique in order to improve the SNR for better estimation of horizontal wind.

However, the analysis in this paper is valid only for the EAR multichannel system, which uses USRP X300 as the digital receiver. We may conclude that, with the current multichannel system, increasing the receiving antenna aperture size does not provide significant improvement. It also indirectly reduces the separation distance between the receiving antennas which leads to another issue – underestimation of the horizontal wind. The use of a directional coupler, though advantageous in retaining the original

EAR single receiver system, could be one of the key factors to be considered in future works developing a EAR multichannel system.

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

The objective of this study was to develop a multichannel receiver system for the EAR, hence enabled spaced-antenna method for horizontal wind observations. This thesis presented the details of the development and performance of the multichannel receiver by means of software-defined radio technique utilizing USRP X300 devices as the hardware platform for digital conversion of the received signals, with the combination of GNU radio as the software platform for processing the signals. The multichannel receiver system has been successfully tested to work simultaneously with the existing standard observation of the EAR.

In Chapter 1, general introductions regarding the radar techniques and the background of research were described. The purpose was to develop understanding about the research motivation, objectives and scope of works. Radar for atmospheric observation, specifically, take advantage of the fluctuation of radio refractive index to receive radar echo. EAR, as one of the atmospheric radars responsible for observing equatorial atmosphere, was established to better understand the coupling processes due to active convective motion in the region, which actively influence the global energy circulation. EAR, however, has only a single receiving channel, thus, it becomes one of the motivating factors for an

upgrade to a multichannel receiving system, while the use of software-defined technique in the development, enabled design flexibility for future improvement.

In Chapter 2, literature reviews on several topics involved in this research were presented. This include the EAR and its capabilities, software-defined radio, GNU radio, USRPs and its daughterboards. With a single channel system, the EAR has already established as a reliable tool for atmospheric observations as deliberated in previous articles and researches, which adopts a few observation techniques, including Doppler beam swinging (DBS), range imaging (RIM) and radio acoustic sounding system (RASS). Next, the examples of previous works, which applied the software-defined radio in their intended applications, convinced that it can be adopted to radar system, in which it provides flexibility in the system design, and at considerably lower cost compared to the conventional radar hardware modification. Lastly, spaced-antenna (SA) method was presented in this chapter as one of the established method with a wide range of applications, but with its own advantages and disadvantages to be considered.

In Chapter 3, the development of software-defined multichannel receiver for EAR was presented, which include the software and hardware setup, configuration of test observations, the signal processing, and the initial results. Currently, the EAR is capable of receiving signals from four channels simultaneously. Channels synchronization was achieved using OctoClock, that provided 10 MHz reference clock and 1 pulse per second (PPS) signal to all channels. The phase difference between channels, although not perfectly synchronized, was sufficient. Directional coupler was utilized during the test observations for splitting received echo signals towards existing system of the EAR, and to the newly installed multichannel receiver (USRP X300s), thus, enabled simultaneous observations of two different systems. The signals received by the USRP X300s were digitized before transferred to the host computer as IQ signals. Post processing, that was carried out to the stored data using full correlation analysis (FCA), revealed that the maximum observable height only reached up to about 8 km height, therefore, requires subsequent works to find out the factors that limit its performance.

In Chapter 4, performance analysis of the multichannel receiver was presented, which includes five different orientations that have been experimented for the application of spaced-antenna method. The analysis consider the size of receiving antenna and its separation distance, by increasing the number of antenna groups, which formed triangular,

spatially separated receiving antennas (by considering the point at the center). Further, phase adjustment was carried out to improve channels synchronization, by taking advantage of the transmitted pulse leaked to the receiver, in real time. The horizontal wind profiles, using Full Correlation Analysis (FCA), were estimated and compared with the standard EAR data. Few samples from all five configurations also have been compared in term of their Doppler spectra, and the horizontal winds, estimated from the FCA. The results show that maximum observable height could only reach about 10 km height, regardless of the aperture size of the receiving antennas. The linear regression analyses show that slight advantage was achieved from the configuration with the largest aperture size. Based on the results, this research provides at least two general validations for the feasibility of a multichannel receiver using USRP for the EAR. Firstly, the EAR system shall requires a different approach of data acquisition in order to increase the SNR. Such improved signals can then be fed into USRP for adopting software-defined radar system. Secondly, due to considerably lower transmit power (i.e., one tenth) compared to the MU radar, the increase in the aperture size of the receiving antenna, with the current system, will only provide slight improvement to the overall performance. Notwithstanding with its drawback in not achieving good SNR, the encouraging results could be extended in the future works, for adopting spaced-antenna method in the atmospheric observation applications.

Lastly, Chapter 5 concludes all important points and summarizes each chapters included in this thesis.

5.2 Recommendations

The number of channels available on the EAR multichannel system can be increased, based on the capacity of host computer to receive and process data simultaneously. It is made available due to the reduction in the data size ($1/1000$) after real time processing is implemented. Future works involving more channels (i.e., eight channels or more), after the improvement on the signals acquisition part is carried out, would certainly provides more interesting results.

Further, the EAR multichannel receiver using USRP X300 shows lower SNR compared to the standard EAR measurement. For example, SNR measured from standard EAR

on September 26, 2019, between 18:00 and 19:00 LT shows variation between 22 dB and 38 dB for height range between 2 km and 6.5 km. Meanwhile, the multichannel receiver recorded SNR between 12 dB and 24 dB for the same period, height range, and aperture size of the receiving antenna. Therefore, SNR improvement of about 10 dB to 14 dB is required for future implementation of software-defined multichannel receiver on the EAR.

Room for improvement for using USRP X300 is still available in the form of RF network on chip (RFNoC), which is not explored in this research. It enables data processing stages to be transferred to each FPGA contained in the USRP X300 and thus, reducing the processing load by host computer. Such implementations allow for more signals processing technique to be performed, such as for mitigating high fluctuation of horizontal wind estimated from FCA method, and to a further extend, spatial domain interferometry, without sacrificing the speed of the processing.

Appendix A

Full Correlation Analysis Principles and Equations

The configuration used for the spaced antenna measurement is depicted in Figure A.1. The movement of diffraction pattern as it passed across the three receiving antenna is visualized as shown in Figure A.2.

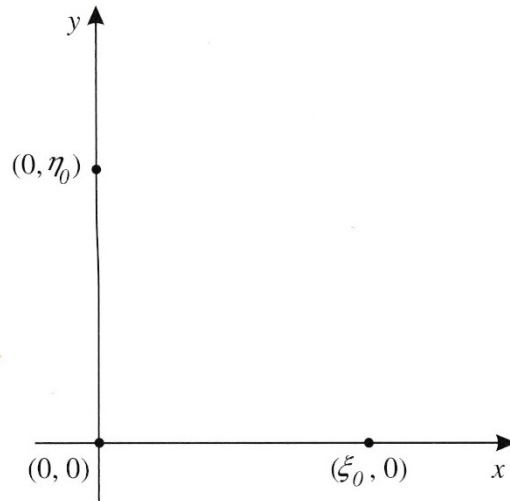


FIGURE A.1: Possible antenna configuration for use in spaced antenna measurements.

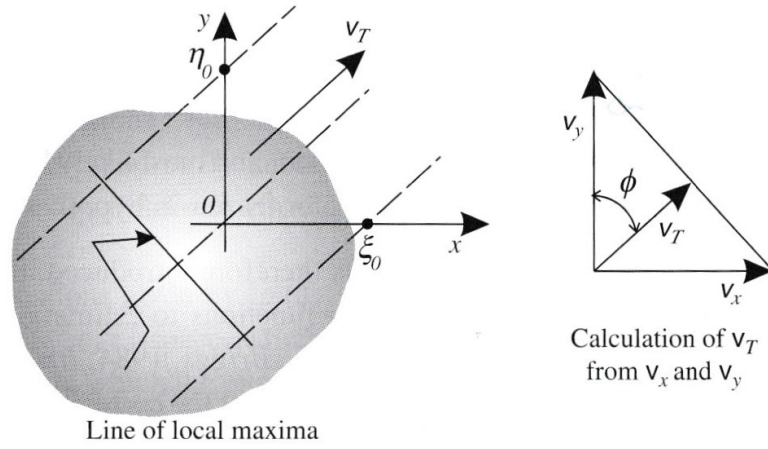


FIGURE A.2: A diffraction pattern projected onto the ground as it passes over the receiving antennas located at $(0, 0)$, $(\xi_0, 0)$, and $(0, \eta_0)$.

The time taken for the line of maximum to pass from origin to both antennas are expressed as:

$$t_x = \frac{\xi_0 \sin \phi}{v_T} \quad (\text{A.1})$$

$$t_y = \frac{\eta_0 \cos \phi}{v_T} \quad (\text{A.2})$$

If the value of t_x and t_y are measured, v_T and ϕ can be found as:

$$v_T = v_x \sin \phi = v_y \cos \phi \quad (\text{A.3})$$

and

$$\phi = \tan^{-1} \frac{v_y}{v_x} \quad (\text{A.4})$$

where $v_x = \xi_0/t_x$ and $v_y = \eta_0/t_y$.

In Full Correlation Analysis (FCA), auto- and cross-correlation functions are used to estimate the wind velocity so that; 1. The diffraction pattern that is projected onto the ground can be systematically elongated in a direction not necessarily either perpendicular or parallel to the mean flow of the wind, and 2. The diffraction patterns in reality can, and most likely will, evolve over time. The correlation function is normalized to unity and expressed as:

$$\underline{\rho}(\xi, \eta, \tau) = \frac{E\{\underline{s}(x + \xi, y + \eta, t + \tau)\underline{s}^*(x, y, t)\}}{E\{|\underline{s}(x, y, t)|^2\}} \quad (\text{A.5})$$

To satisfy the relevant properties of the correlation function, equation (A.5) is constructed as:

$$|\underline{\rho}(\xi, \eta, \tau)| = f(A\xi^2 + B\eta^2 + C\tau^2 + 2F\xi\tau + 2G\eta\tau + 2H\xi\eta) \quad (\text{A.6})$$

where parameters A through H are used to describe the shape of the ellipsoidal auto-correlation functions. Considering for the temporal evolution of the correlation function where the illustration is depicted in Figure A.3, equation (A.6) is further modified into:

$$|\underline{\rho}(\xi, \eta, \tau)| = f(A(\xi - V_x\tau)^2 + B(\eta - V_y\tau)^2 + K\tau^2 + 2H(\xi - V_x\tau)(\eta - V_y\tau)) \quad (\text{A.7})$$

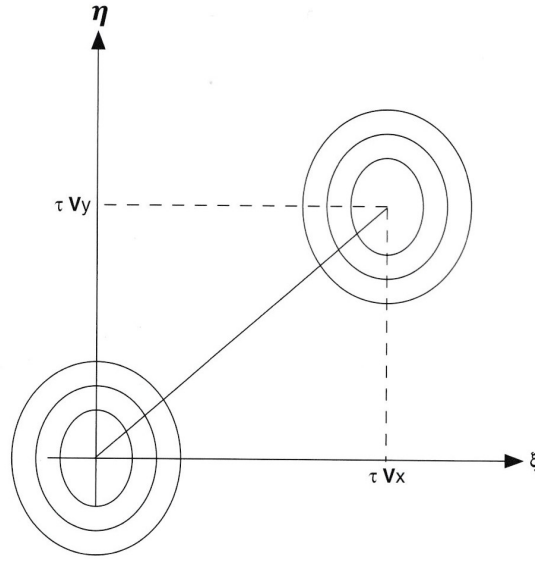


FIGURE A.3: Translation of an atmospheric diffraction pattern along the ground and how the trace velocity of the pattern can be calculated.

By equating the similar terms, the parameters A through H can be solved as follow:

$$AV_x + HV_y = -F \quad (\text{A.8})$$

$$HV_x + BV_y = -G \quad (\text{A.9})$$

$$K = C - AV_x^2 - BV_y^2 - 2HV_xV_y \quad (\text{A.10})$$

If we consider the arrangement of three antennas on the ground forming a triangle as in Figure A.1, the autocorrelation taken at lags $\xi = \xi_0$ and $\eta = 0$ can be written as:

$$|\underline{\rho}(\xi_0, 0, \tau)| = f(A\xi_0^2 + C\tau^2 + 2F\xi_0\tau) \quad (\text{A.11})$$

This expression attains a maximum value at $\tau = \tau'_x$ thus, the derivation of equation (A.11) with respect to τ and equating to zero produces:

$$\tau'_x = -\frac{F}{C}\xi_0 \quad (\text{A.12})$$

Likewise, the autocorrelation at lags $\xi = 0$ and $\eta = \eta_0$ is written as:

$$|\underline{\rho}(0, \eta_0, \tau)| = f(B\eta_0^2 + C\tau^2 + 2GF\eta_0\tau) \quad (\text{A.13})$$

and the resulting derivation with respect to τ and equating to 0 gives:

$$\tau'_y = -\frac{G}{C}\eta_0 \quad (\text{A.14})$$

The remaining parameter can be obtained by assuming that the auto- and cross-correlations have the same functional forms. The average of autocorrelation function at each of the three antennas is expressed as $\underline{\rho}(0, 0, \tau)$. Then, the temporal lag τ_x is define such that:

$$|\underline{\rho}(\xi_0, 0, 0)| = |\underline{\rho}(0, 0, \tau_x)| \quad (\text{A.15})$$

and is illustrated in Figure [A.4](#)

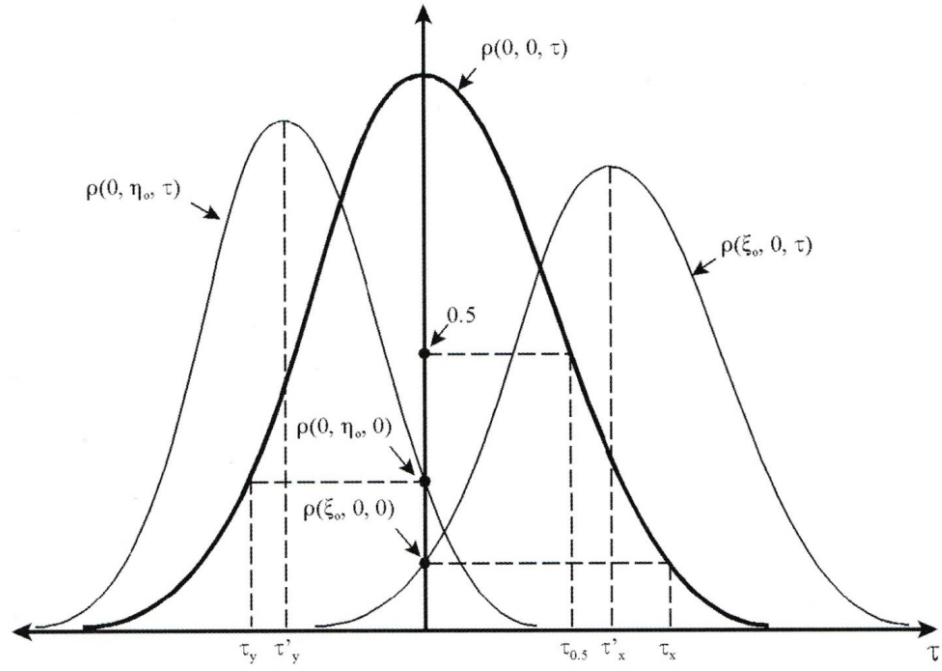


FIGURE A.4: Representation of the correlation function along with some of the parameters derived from them, which are used in FCA calculations.

The equality holds when:

$$A\xi_0^2 = C\tau_x^2 \quad (\text{A.16})$$

or

$$\tau_x^2 = \frac{A}{C}\xi_0^2 \quad (\text{A.17})$$

Similarly, τ_y can be defined such that:

$$|\underline{\rho}(0, \eta_0 0)| = |\underline{\rho}(0, 0, \tau_y)| \quad (\text{A.18})$$

which lead to:

$$B\eta_0^2 = C\tau_y^2 \quad (\text{A.19})$$

or

$$\tau_y^2 = \frac{B}{C}\eta_0^2 \quad (\text{A.20})$$

Finally, τ_{xy} is defined by:

$$|\underline{\rho}(\xi_0, \eta_0 0)| = |\underline{\rho}(0, 0, \tau_{xy})| \quad (\text{A.21})$$

which results in:

$$A\xi_0^2 + B\eta_0^2 + 2H\xi_0\eta_0 = C\tau_{xy}^2 \quad (\text{A.22})$$

or

$$\tau_{xy}^2 = 2\xi_0\eta_0\frac{H}{C} + \xi_0^2\frac{A}{C} + \eta_0^2\frac{B}{C} \quad (\text{A.23})$$

Appendix B

Functions Used for Phase Correction

The real time processing is implemented in C++, retaining most of the flow as in the initial development of multichannel receiver, described in Chapter 3.

In Chapter 4, real time signal processing flow is summarized. The additional function for phase adjustment, applied in the real time processing, is shown in the following pages.

```

#define NCHAN 4
#define MAXIPP 1600
#define SampleRate 5 // Sample Rate [MHz]

/////////////////////////////////////////////////////////////////
bool skip_tx(ShmAddr ** shm, int nskip[]) {
    int nflag = 0, ic;
    bool flag[NCHAN] = {};

    cout << "=== skip_tx() ===" << endl;

    for(ic = 0; ic < NCHAN; ic++) {
        nskip[ic] = 0;
    }

    while (nflag < NCHAN) {
        for(ic = 0; ic < NCHAN; ic++) {
            if(flag[ic]) continue;

            if(rxmax[0] > 0 && rxmax[ic] < rxmax[0] * 5.) {
                if(CF_abs_greater(datawait(shm[ic], MAXIPP * SampleRate), MAXIPP *
SampleRate, SampleRate - 1, rxmax[ic] * 0.9)) {
                    shm[ic]->start = ShmAdd(shm[ic], MAXIPP * SampleRate);
                    nskip[ic] += MAXIPP * SampleRate;
                } else {
                    flag[ic] = true;
                    nflag++;
                }
            } else {
                if(! istxoff(datawait(shm[ic], MAXIPP * SampleRate), MAXIPP * SampleRate))
{
                    shm[ic]->start = ShmAdd(shm[ic], MAXIPP * SampleRate);
                    nskip[ic] += MAXIPP * SampleRate;
                } else {
                    flag[ic] = true;
                    nflag += 1;
                }
            }
        }
    }

    if(isum(nskip, NCHAN) == 0)
        return(true);

    cout << "skip_tx(): nskip =";
    for(ic = 0; ic < NCHAN; ic++)
        cout << " " << nskip[ic];
    cout << endl;

    nskipbalance(shm, nskip, NCHAN);

    return(false);
}

/////////////////////////////////////////////////////////////////
bool skip_tx_gap(ShmAddr ** shm, int nskip[]) {
    int nflag = 0, iskip, ic;
    bool flag[NCHAN] = {};
    ComplexFloat *data;

    cout << "=== skip_tx_gap() ===" << endl;

    for(ic = 0; ic < NCHAN; ic++)
        nskip[ic] = 0;

```

File: /home/norazlan/Desktop/appendix_func.cpp

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```

while(nflag < NCHAN) {
    for(ic = 0; ic < NCHAN; ic++) {
        if(flag[ic]) continue;

        if(rxmax[0] > 0 && rxmax[ic] < rxmax[0] * 5.) {
            if(CF_abs_greater(datawait(shm[ic], MAXIPP * SampleRate), MAXIPP *
SampleRate, SampleRate - 1, rxmax[ic])) {
                flag[ic] = true;
                nflag++;
            } else {
                shm[ic]->start = ShmAdd(shm[ic], MAXIPP * SampleRate);
                nskip[ic] += MAXIPP * SampleRate;
            }
        } else {
            if(istxoff(datawait(shm[ic], MAXIPP * SampleRate), MAXIPP * SampleRate)) {
                shm[ic]->start = ShmAdd(shm[ic], MAXIPP * SampleRate);
                nskip[ic] += MAXIPP * SampleRate;
            } else {
                flag[ic] = true;
                nflag += 1;
            }
        }
    }
}

for(ic = 0; ic < NCHAN; ic++) {
    if(rxmax[0] > 0 && rxmax[ic] < rxmax[0] * 5.) {
        if(! CF_abs_greater(datawait(shm[ic], ipp * SampleRate), ipp * SampleRate,
1, rxmax[ic])) {
            cout << "skip_tx_gap(): rxmax[" << ic << "] = " << scientific << rxmax[ic]
<< " data max = " << CF_abs_max(datawait(shm[ic], ipp * SampleRate), ipp *
SampleRate) << endl;

            shm[ic]->start = ShmAdd(shm[ic], ipp * SampleRate);
            nskip[ic] += ipp * SampleRate;
        }
    } else {
        if(istxoff(datawait(shm[ic], ipp * SampleRate), ipp * SampleRate)) {
            shm[ic]->start = ShmAdd(shm[ic], ipp * SampleRate);
            nskip[ic] += ipp * SampleRate;
        }
    }
}

if(isum(nskip, NCHAN) == 0)
    return(true);

for(ic = 0; ic < NCHAN; ic++) {
    data = datawait(shm[ic], ipp * SampleRate);
    for(iskip = 0; iskip < ipp * SampleRate; iskip++) {
        if(abs(*data++) > rxmax[ic])
            break;
    }

    shm[ic]->start = ShmAdd(shm[ic], iskip);
    nskip[ic] += iskip;
}

nskipbalance(shm, nskip, NCHAN);

return(false);
}

```


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List of Publications

Refereed Journals

1. N. A. M. Aris, L. Luini, J. Din, and H. Y. Lam. 1-Minute Integrated Rain Rate Statistics Estimated from Tropical Rainfall Measuring Mission Data. *IEEE Antennas and Wireless Propagation Letter*, 12: 132–135, 2013.
2. N. A. M. Aris, H. Hashiguchi, and M. Yamamoto. Development of Software-Defined Multichannel Receiver for EAR. *Radio Science*, 54(7): 671–679, 2019. doi: 10.1029/2019RS006817.
3. N. A. M. Aris, H. Hashiguchi, and M. Yamamoto. Comparison of EAR Spaced-Antenna Performance Using Multiple Orientation of Receiving Antennas (*submitted to Radio Science*)

Unrefereed Article

1. N. A. M. Aris. Introduction to My Research. *Information Magazine of EE Department, cue*, 42, page 64, September 2019. url: <https://www.s-ee.t.kyoto-u.ac.jp/ja/information/cue>

Presentations

1. N. A. M. Aris, H. Hashiguchi, and M. Yamamoto. Development of EAR Multi-Channel Receiver System Using Software Defined Radio. 15th International Workshop on Technical and Scientific Aspects of MST radar (MST15/iMST2), at National Institute of Polar Research, Tachikawa, Tokyo. May 26 – 31, 2017.
2. N. A. M. Aris, H. Hashiguchi, and M. Yamamoto. Development of EAR Multi-Channel Receiver System Using Software Defined Radio. 2nd Asia Research Node Symposium on Humanosphere Science (The 343rd Symposium for Sustainable Humanosphere), at Kyoto University, Uji, Kyoto. July 19 – 21, 2017.
3. N. A. M. Aris, H. Hashiguchi, and M. Yamamoto. Development of Software-Defined Multi-Channel Receiver System for the Equatorial Atmosphere Radar (EAR). 11th MU radar Equatorial Atmosphere Radar Symposium, at Kyoto University, Uji, Kyoto. Sept. 7 – 8, 2017.
4. N. A. M. Aris, H. Hashiguchi, and M. Yamamoto. Development of Software-Defined Multi-Channel Receiver System for the Equatorial Atmosphere Radar (EAR). International Symposium on Earth-Science Challenges (ISEC), at Kyoto University, Uji, Kyoto. October 1 – 5, 2017.
5. N. A. M. Aris, H. Hashiguchi, and M. Yamamoto. Development of Software-Defined Multi-Channel Receiver System for the Equatorial Atmosphere Radar (EAR). Society of Geomagnetism and Earth, Planetary and Space Sciences (SGEPSS) domestic meeting, at Kyoto University, Uji, Kyoto. October 16 – 19, 2017.
6. N. A. M. Aris, H. Hashiguchi, and M. Yamamoto. Development of Software-Defined Multi-Channel Receiver System for the Equatorial Atmosphere Radar (EAR). Humanosphere Science School (HSS), at Bogor, Indonesia. November 1 – 2, 2017.
7. N. A. M. Aris, H. Hashiguchi, and M. Yamamoto. Development of Software-Defined Multi-Channel Receiver System for the Equatorial Atmosphere Radar (EAR). Japan Geoscience Union Meeting (JpGU) 2018, at Makuhari Messe, Chiba, Japan. May 20 – 24, 2018.

8. N. A. M. Aris, H. Hashiguchi, and M. Yamamoto. Development of Software-Defined Multi-Channel Receiver System for the Equatorial Atmosphere Radar (EAR). The 3rd Asia Research Node (ARN) Symposium on Humanosphere Science, at National Chung Hsing University, Taiwan. September 25 – 27, 2018.
9. N. A. M. Aris, H. Hashiguchi, and M. Yamamoto. Analysis of Equatorial Atmosphere Radar (EAR) Spaced-Antenna Performance from Multiple Orientation of the Receiving Antennas. 39th International Conference on Radar Meteorology, at Nara Kasugano International Forum IRAKA, Nara, Japan. September 16 – 20, 2019.
10. N. A. M. Aris, H. Hashiguchi, and M. Yamamoto. Development of Software-Defined Multichannel Receiver System for Equatorial Atmosphere Radar (EAR). Atmospheric Seminar, at Research Institute for Sustainable Humanosphere (RISH), Kyoto University, Uji, Kyoto. December 20, 2019.