CLUTTER MODELING AND MOVING TARGET DETECTION WITH PASSIVE BISTATIC RADAR FOR MILITARY USE

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İBRAHİM ETHEM YILMAZ

Prof. Dr. Necmi Serkan TEZEL

CLUTTER MODELING AND MOVING TARGET DETECTION WITH PASSIVE BISTATIC RADAR FOR MILITARY USE

İbrahim Ethem YILMAZ

Karabuk University
Institute of Graduate Programs
Electric-Electronic Engineering Department
Prepared as
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Prof. Dr. Necmi Serkan TEZEL

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I certify that in my opinion the thesis submitted by İbrahim Ethem YILMAZ titled "CLUTTER MODELING AND MOVING TARGET DETECTION WITH PASSIVE BISTATIC RADAR FOR MILITARY USE" is fully adequate in scope and in quality as a thesis for the degree of Master of Science.

Prof. Dr. Necmi Serkan TEZEL ....

Thesis Advisor, Department of Electric-Electronic Engineering

This thesis is accepted by the examining committee with a unanimous vote in the Department of Electric-Electronic Engineering as a master of science thesis. 03/01/2022

Examining Committee Members (Institutions)		Signature
Chairman	: Doç. Dr. Turgut ÖZTÜRK (BTÜ)	....
Member	: Prof. Dr. Necmi Serkan TEZEL (KBÜ)	....
Member	: Doç. Dr. Ziyodulla YUSUPOV (KBÜ)	....

The degree of Master of Science by the thesis submitted is approved by the Administrative Board of the Institute of Graduate Programs, Karabuk University.

Prof. Dr. Hasan SOLMAZ ....

Lisansüstü Eğitim Enstitüsü Müdürü

"All the information in this thesis has been obtained and presented in accordance with academic rules and ethical principles; I further declare that I have made all attributions that do not originate in this work, as required by these rules and principles."

İbrahim Ethem YILMAZ

ÖZET

Yüksek Lisans Tezi

ASKERİ KULLANIMA UYGUN PASİF BİSTATİK RADARDA KARGAŞA YOK ETME VE HAREKETLİ HEDEF TESPİTİ

İbrahim Ethem YILMAZ

Karabük Üniversitesi
Lisansüstü Eğitim Enstitüsü
Elektrik-Elektronik Mühendisliği Anabilim Dalı

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Monostatik eşdeğerlerine kıyasla pasif bistatik radarlar iki özelliği ile ön plana çıkmaktadırlar. Bunlardan ilki alıcı ve verici devrelerinin farklı konumlarda olmasıdır. Bu geometrik farklılık pasif radarlara gizli hedeflere karşı etkinlik ve gizlilik gibi birtakım avantajlar sağlamaktadır. Ön plana çıkan diğer özelliği ise aktif radarların aksine kendilerine ait vericilerinin bulunmamasıdır. Hali hazırda yayın yapan ve fırsat aydınlatıcısı olarak adlandırılan vericileri kullanırlar. Bu şekilde bir verici kullanmaları sebebiyle fark edilmeden operasyonlarını yürütme işlevine sahiptirler. Pasif bistatik radarlar bu avantajlarının sonucu olarak askeri ve sivil alanlarda popülerlik kazanmıştır.

Pasif radarların kendilerine ait alıcılarının olmaması bazı dezavantajları da beraberinde getirmektedir. İletilen sinyalin radar tarafından kontrol edilememesi sinyal işleme açısından pasif bistatik radar konseptini kompleks bir hale getirmektedir. Çevresel faktörlerin oluşturduğu ve sinyalin hedef dışındaki cisimlerden yansımasından kaynaklanan kargaşa sinyali de karmaşıklığı artıran en önemli etmenlerdendir. Dolayısıyla hedef tespitinde problem oluşturmaktadır.

Pasif radarlarda iletilen sinyalin kontrol edilmemesinden dolayı darbe sıkıştırma aşamasında geleneksel filtre kullanımına uygun değildir. Geleneksel filtreler zamanla değişen yapıda sinyaller üretmekte olup pasif radar amaçlarına hizmet etmemektedir. Bu nedenle uyumlu veya karşıt filtre gibi zamanla değişmeyen yapıda filtreler kullanılmalıdır. İlk olarak sinyal içerisinde istenmeyen kargaşayı bastırmak ve hedef tespitinin yapılmasını sağlamak için darbe skıştırma aşamasında uyumlu filtre kullanıldı. İkinci olarak huzme şekillendirme yöntemi kullanılarak sinyalin amaçlara uygun şekilde kullanılabilmesi sağlandı. Farklı kargaşa-gürültü oranlarının ve hüzme şekillendirme aşamasında anten sayısının geliştirme faktörüne olan etkileri incelendi. Doppler frekansının 0 Hz olduğu yani tespit edilen nesnenin hareketsiz davranışı sebebiyle kargaşa sinyali oluşturduğu kısımlarda kargaşa bastırıldı. Doppler frekansı ekseninde hareketli hedeflerin geliştirme faktörü üzerinden tespit edilebilir oldukları gösterildi.

Anahtar Sözcükler : Pasif Bistatik Radar, Kargaşa Modelleme, Hareketli Hedef Tespiti

Bilim Kodu : 90524

ABSTRACT

M. Sc. Thesis

CLUTTER MODELING AND MOVING TARGET DETECTION WITH PASSIVE BISTATIC RADAR FOR MILITARY USE

İbrahim Ethem YILMAZ

Karabük University
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Compared to their monostatic equivalents, passive bistatic radars stand out with two features. The first of these is that the receiver and transmitter circuits are in different positions. This geometric difference provides passive radars with some advantages such as efficiency and stealth against hidden targets. Another prominent feature is that unlike active radars, they do not have their own transmitters. The system uses transmitters that are already broadcasting, called illuminator of opportunity. Because it uses a transmitter in this way, they have the function of conducting their operations undetected. Passive bistatic radars have gained popularity in military and civilian areas as a result of these advantages.

Passive radars do not have their own receivers, which also brings some disadvantages. The fact that the transmitted signal cannot be controlled by the radar complicates the passive bistatic radar concept in terms of signal processing. The clutter signal created by environmental factors and caused by the reflection of the signal from objects other than the target is also one of the most important factors that increase the complexity. Therefore, it causes a problem in target detection.

Since the transmitted signal is not controlled in passive radars, it is not suitable for the use of conventional filters in the pulse compression stage. Conventional filters generate time-varying signals and do not serve passive radar purposes. For this reason, filters that do not change over time, such as match or reciprocal filters, should be used. First, a matched filter was used in the pulse compression stage to suppress unwanted clutter in the signal and to ensure target detection. Secondly, by using the beamforming method, it was ensured that the signal could be used in accordance with the purposes. The effects of different Clutter-to-Noise Ratios (CNR) and the number of antennas in the beamforming phase on the improvement factor were investigated. The clutter was suppressed in the parts where the Doppler frequency was 0 Hz, that is, the clutter signal was generated due to the motionless behavior of the detected object. It has been shown that moving targets on the Doppler frequency axis can be detected through the improvement factor.

Key Words : Passive Bistatic Radar, Land Clutter Modelling, Moving Target Detection

Science Code : 90524

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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

Hz : hertz

kHz : kilohertz

MHz : megahertz

GHz : gigahertz

m : meter

km : kilometer

mW : milliwatt

kW : kilowatt

MW : megawatt

dB : decibel

R_T : distance between Tx and T

R_R : distance between Rx and T

R_B : bistatic range

L : distance between Tx and Rx

δ : angle between target velocity vector and bistatic bisector

θ_T : Tx pointing angle

θ_R : Rx pointing angle

β : bistatic angle

t : time

τ : delay

c : speed of light

ΔR : monostatic range resolution

ΔR_B : bistatic range resolution

BW : bandwidth

P_R : received signal power

P_N : receiver noise power

P_T : transmitted power

G_T : transmitter antenna gain

R_T : transmitter to target range

σ_B : target bistatic radar cross-section

R_R : target to receiver range

G_R : receiver antenna gain

λ : signal wavelength

k : Boltzmann's constant

T_0 : 290K, noise reference temperature

F : receiver effective noise figure

L_o : system losses

F_T : Tx to T propagation factor

F_R : Rx to T propagation factor

L_T : Tx system losses

L_R : Rx system losses

B_N : Rx noise bandwidth

f_D : Doppler shift

v_T : target velocity

V : bistatic velocity

d : distance between surveillance antennas

τ_0 : bistatic propagation delay

B : number of pieces in a CPI

ϕ_r : angular spacing

α : angle of incidence

W_i : weighting vector

f_T : carrier frequency

F_s : sampling frequency

R : range interval number

L_N : number of sample in one batch

T : duration of one batch

n : number of surveillance antennas

ABBREVIATIONS

AM	: Amplitude Modulation
AWGN	: Additive White Gaussian Noise
BR	: Bistatic Radar
CNR	: Clutter-to-Noise Ratio
CW	: Continuous Wave
CPI	: Coherent Processing Interval
DAB	: Digital Audio Broadcasting
DFT	: Discrete Fourier Transform
DSI	: Direct Path Interference
DVB-T	: Digital Video Broadcasting-Terrestrial
DVB-S	: Digital Video Broadcasting-Satellite
FM	: Frequency Modulation
GSM	: Global System for Mobile Communications
IDFT	: Inverse Discrete Fourier Transform
IF	: Improvement Factor
KH	: Klein Heidelberg
MPI	: Multipath Interference
OFDM	: Orthogonal Frequency Division Multiplexing
PARADE	: Passive Radar Demonstrator
PBR	: Passive Bistatic Radar
PCL	: Passive Coherent Location
PCR	: Passive Covert Radar
RA	: Reference Antenna
Rx	: Receiver
SA1	: 1^{st} Surveillance Antenna
SA2	: 2^{nd} Surveillance Antenna
SA3	: 3^{rd} Surveillance Antenna
SA4	: 4^{th} Surveillance Antenna
SA5	: 5^{th} Surveillance Antenna
SFN	: Single Frequency Network

SNR : Signal-to-Noise Ratio

T : Target

Tx : Transmitter

UHF : Ultra High Frequency

VHF : Very High Frequency

Wi-Fi : Wireless Fidelity

WWII : World War II

Tx : Transmitter

CHAPTER 1

INTRODUCTION

Radar (Radio Detection and Ranging) is a system that uses various electromagnetic waves to determine target detection and the range of that target. The system also find velocity, direction, elevation angle such parameter defined by the target. While the radar provides the acquisition of the relevant parameters, in operational point of view, radar principle is similar to sound-wave reflection. Unlike sound-wave reflection, radar uses much wider range of frequency for transmit energy in electromagnetic spectra. A portion of the reflected energy from the target evaluate by the system for determine target parameters.

It is possible to evaluate radar circuits according to the receiver and transmitter geometry. From this perspective, the type of radar where the receiver and transmitter circuits are in the same location is called monostatic radar. This type of radar uses its own transmitter for surveillance, target detection or any other purposes. The target distance to be determined is founded by calculating the time elapsed in this process as a result of the signal transmitted through the transmitting antenna reflecting from the target to the receiving antenna. On the other hand, there are radars with bistatic geometry, which have their own transmitter in the same way as monostatic radars, but whose geometry is different from the monostatic geometry, the positions of the receiving and transmitting antennas are not the same. In bistatic geometry, radar's receiving site (one antenna or multiple antennas) utilizes two signals; one of them is directly from transmitter and the other is reflected from the target. The target range is found by calculating the delay between the signals. Bistatic radars also have transmitter of its own.

There are passive radars (PR) that operate in bistatic geometry however these radars do not have a transmitter of their own. This type of radar is also known as passive covert location (PCL) radar, passive covert radar (PCR). They take advantage of the illuminators of opportunity or non-cooperative illuminators that are already broadcasting and commonly commercial transmitters such as FM radio, Analog TV, digital audio broadcasting (DAB), digital video broadcasting-terrestrial (DVB-T), direct video broadcasting-satellite (DVB-S) TV, GSM telephone signals, Wi-Fi signals etc.

Considering its features and different approach in application, passive radar has advantages and disadvantages compared to active radar systems. Passive radar potential attractions:

- Since the transmitters of the opportunity illuminators used are generally in high locations, therefore PR have broad coverage.
- The cost of system is much lower than active radar because it does not have any transmitter expenditure.
- Well suited for covert operations as the receiver does not emit signals.
- Difficulty of jamming against PR.
- Excess of illuminator of opportunity that can be used.

In contrast with advantages:

- The computational overhead of adapting the waveform for radar purposes.
- Dependency on the transmission source.
- Direct Signal Interference (DSI) and Multipath Interference (MPI) effects because of continuous waveform of signal.
- Low range and doppler resolution for targets close to the baseline.

One of the biggest problems encountered while detecting targets in passive bistatic radar systems is the difficulty in detecting the weak echo signal reflected from the target due to the clutter function caused by environmental factors (sea waves, trees, skyscrapers etc.) [1-8]. In this study, clutter was filtered and used for target detection in a bistatic radar system using an FM illuminator as a transmitter.

1.1. BACKGROUND AND MOTIVATION

The Daventry Experiment, the first passive radar experiment conducted by Robert Watson Watt and Arnold Wilkins in 1935, showed that radar detection of aircraft at useful ranges was possible by detecting the Heyford bomber aircraft at a range of 8 km via a BBC transmitter operating at 6 MHz [9-11]. It paved the way for the Chain Home radar system, as it was shown as a potential solution against possible raids by the enemy. It will be the backbone of the British air defense system in World War II [12].

Before and after the World War II is an important period for the development of radar technologies. At this period various countries enhanced their knowledge and defense systems by working on radar. During the WWII Germans used a passive bistatic radar (PBR) namely Klein Heidelberg (KH) that utilizes British air defense system Chain Home as an illuminator of opportunity. Using a physically large antenna array, the KH (30 m high × 22 m wide) was also deployed in multiple regions and used as an important early warning system, providing a wide coverage area to the Germans [12].

In the 1950s and 1960s, studies on passive bistatic radar were limited due to the insufficiency of data processing capability and information privacy policies during the cold war period [1,11]. However, cooperative bistatic radar studies such as the American AN/FPS-23 early warning system and the AN/FPS-133 Air Force Space Surveillance System have been developed. These systems were produced for a certain purpose. Active monostatic radar was the mainstream of radar studies [13].

By the 1980s and 1990s, passive location began to increase its popularity in the fields of scientific and defense systems because of developments of data processing and the emergence more suitable receiver circuits. The use of television transmitters as an illuminator of opportunity can also be counted as a turning point [14]. In 1998, a passive radar system called Silent Sentry was developed by U.S. company Lockheed Martin Corporation. It is the first commercial PCR system [9]. This system based on

FM radio illuminators and used for real-time tracking of multiple targets and detection [9,11].

In the last 20 years, the interest in passive radar systems has increased with the advancement of technology and the developments of data processing. Systems such as PARADE, which uses the Russian P18 VHF observation radar as an illuminator, Occiu developed by the French C&T company, HA100 (name comes from the initials of Homeland Alert and 100 km detection range) by Thales, SELEX can be given as examples [9]. Many articles [2,15-27] and books [11,28-30] were published in the field of passive and/or bistatic radar study during this period.

Nowadays, passive radar systems have become a field of study that attracts a lot of attention in both academic and industrial fields due to the features they provide. Factors such as its possibility of detecting stealth targets and its difficulty in detecting increase its potential to be an effective field for the homeland security [1]. My motivation for writing this thesis is to contribute to the increase of studies in this field in our country and the important potential that the PR system can achieve in the defense of the homeland.

1.2. AIMS AND OBJECTİVES

Passive radar has become an important subject of study in military, academic and civilian fields due to its low cost compared to active radars, its effectiveness against hidden targets (due to the fact that the radar cross-section does not decrease compared to its monostatic equivalents), and the benefits of not having a transmitter of its own. However, in addition to these advantageous features, it brings some problems due to reasons such as signal processing complexity. One of these problems is the necessity of suppressing the clutter caused by environmental factors. As clutter may mask moving weak target echo signal, its suppression is crucial for the operation of passive radar.

Another problem that is frequently encountered in passive radars can be shown as the negative effects of not having its own transmitter like active radars. The system needs to provide the transmitter with the help of the already broadcasting illuminators, it requires the signal to be suitable for passive radar purposes. This function is achieved by optimizing the signal with tools such as a matched filter.

Considering these factors, the general objectives of this study can be synthisised as:

- Ensuring that the FM signal model used as the illuminator is brought into the appropriate form by using a match filter.
- Modeling the clutter added to the signal due to environmental factors.
- Suppressing modeled clutter so it doesn't affect target detection.
- Demonstrating the effect of different CNR values and antenna number on the proposed system.
- To demonstrate the feasibility of target detection with the proposed passive bistatic radar system.

1.3. OUTLINE OF THESIS

This thesis consists of five chapters. The first chapter includes the purpose of the thesis, a brief history of passive radar, the motivation for writing the thesis, and the outline of the thesis.

In the Chapter 2, the concept of passive radar and the technical theory behind it are discussed. In addition, the illuminators that can be used by passive radar systems and the evaluation of the characteristics of these illuminators in terms of passive radar are included.

In Chapter 3, the geometry of the designed system and the FM signal model used are described. The match filter used in the pulse compression stage is introduced. Finally, the clutter suppression method is presented.

In Chapter 4, the outputs of the designed system in Doppler space are given over the improvement factor. Results for different system parameters are given and compared.

In Chapter 5, the conclusion and recommendations are included. It gives an idea about future work. Then it ıncludes the authors short resume about educational background.

CHAPTER 2

PASSIVE RADAR BASICS

In this chapter, basic description and background concepts of passive radar has been introduced. These include bistatic geometry, Doppler characteristic of PR, range equation and illuminators of opportunity.

2.1. BISTATIC RADAR

It is important to understand the concept of bistatic radar (BR), as passive bistatic radars are an element of BR systems.

Bistatic radars are systems with a geometry in which the receiving and transmitting antennas are in different locations. These systems use two different types of transmitters. The first of these is the transmitters specially allocated for BR, while the other is the transmitters that are currently broadcasting and are generally used for commercial purposes. Both of these two types of transmitter systems perform target detection by evaluating the echo signal reflected from the target, similar to the monostatic system, but passive systems that use currently broadcasting transmitter as an illuminator need an antenna that receives the signal coming directly from the transmitter in the receiver side. Hence bistatic radar must have at least two receiving channels: reference and echo and they are called passive bistatic radar (PBR) or passive coherent location (PCL) because of this passive characteristic. The absence of its own transmitter and the difference in receiver and transmitter locations gives great advantages to PBR systems. Detection capability against stealth targets, difficulty of jamming etc. Signal processing difficulty created by the absence of a synchronized signal is a disadvantage of PBR Figure 2.1 shows the basic bistatic radar structure.

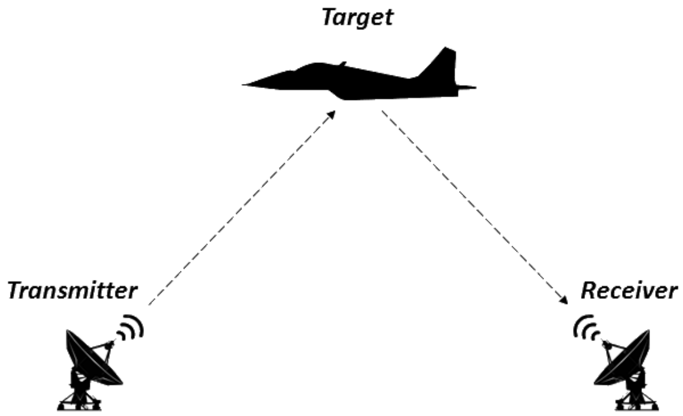


Figure 2.1. Basic bistatic radar structure.

Bistatic radars may differ according to the number of receivers and transmitters, illuminator types and signal modulation.

Table 2.1. Different features used by radar system.

Features	**Different Types Used by BR**
Transmitter or Receiver Numbers	Bistatic, Multistatic
Cooperation of Illuminators	Cooperative, Non-cooperative
Signal Modulation	FM, AM, OFDM, Unmodulated
Operation of Signal	Continuous Wave (CW), Pulsed

2.1.1. Bistatic Radar Geometry

In Figure 2.2, the bistatic radar geometry is depicted in Cartesian coordinates in the transmitter-receiver-target plane [1]. The figure includes receiver (Rx), transmitter (Tx) and target (T).

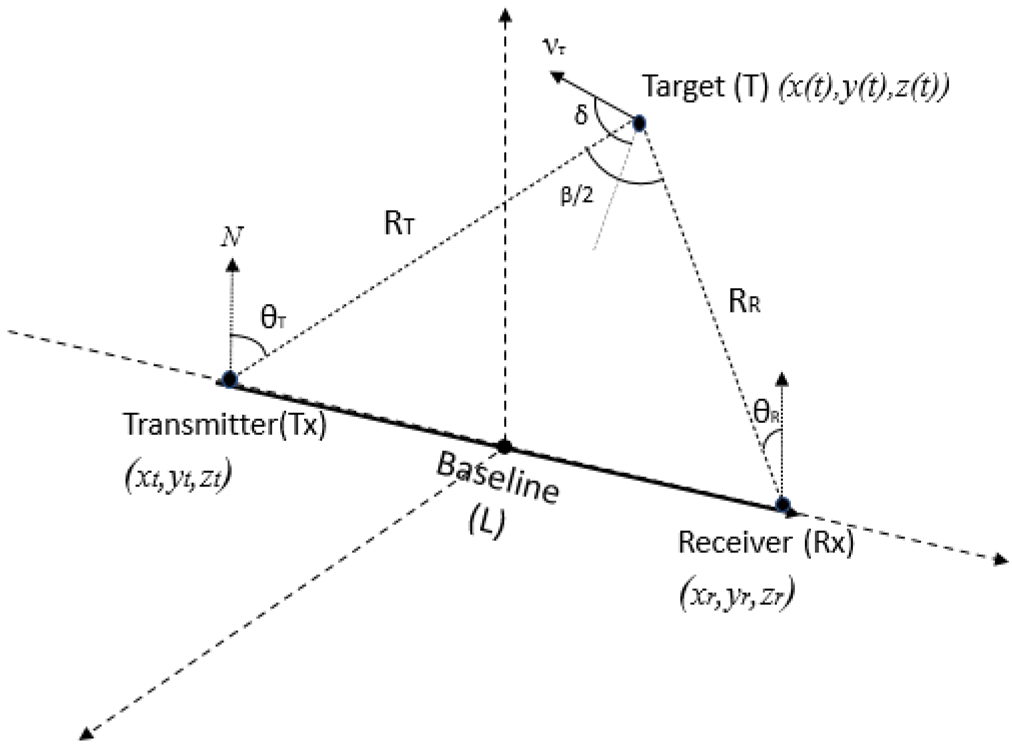


Figure 2.2. Bistatic radar geometry.

The notations of above figure; R_T, R_R and L are distance between Tx and T, distance between Rx and T, distance between Tx and Rx or baseline, respectively. R_T, R_R and L are calculated by using Equation 2.1 in cartesian coordinates.

$$
\begin{aligned}
R_T(t) &= \sqrt{(x(t)-x_t)^2 + \left(y(t)-y_t\right)^2 + (z(t)-z_t)^2} \\
R_R(t) &= \sqrt{(x(t)-x_r)^2 + \left(y(t)-y_r\right)^2 + (z(t)-z_r)^2} \\
L &= \sqrt{(x_t-x_r)^2 + (y_t-y_r)^2 + (z_t-z_r)^2}
\end{aligned} \quad (2.1)
$$

δ is the angle between the target velocity vector and bistatic bisector. θ_T is transmitter-pointing angle and θ_R is receiver-pointing angle. The angle subtended at the target by the transmitter and receiver is β. It is called the bistatic angle and is defined by Equation 2.2.

$$\beta = \theta_T - \theta_R \quad (2.2)$$

2.1.2. Bistatic Radar Range and Range Resolution

In bistatic radars, the bisatic range (R_B) is found by the difference between the indirect path $R_T + R_R$ and the direct path L, as can be defined in Equation 2.3.

$$R_B(t) = R_T(t) + R_R(t) - L \qquad (2.3)$$

Bistatic range also calculated by multiplying τ which is the delay between reference signal and echo signal and the speed of light, as seen in Equation 2.4.

$$R_B = c.\tau \qquad (2.4)$$

Contours of the constant bistatic range $(R_T + R_R)$ define an ellipse, with the transmitter and receiver located at the two focal points. Because of this reason, targets on the same ellipse have the same bistatic range. Its planar representation is given in Figure 2.3.

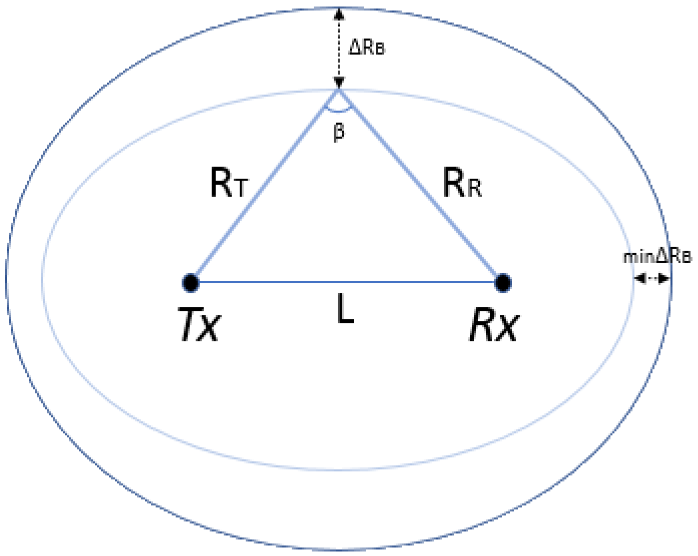


Figure 2.3. Constant bistatic range contours and their range resolution between each other.

Range resolution in bistatic radar is defined as the shortest distance at which two targets can be distinguished from each other. This distance appears as the distance between two concentric ellipses. Due to the shape of the ellipse, this distance changes depending on the β angle. As β approaches zero, the range resolution increases as the distance of ellipses decreases, while when it approaches 180 degrees, the range resolution decreases. The range resolution is shown in Figure 2.3. Monostatic and bistatic range resolutions are expressed in Equation 2.5 below, respectively.

$$\Delta R = \frac{c}{2BW}$$
$$\Delta R_B = \frac{c}{2\cos\left(\frac{\beta}{2}\right)BW} \tag{2.5}$$

In Equation 2.5, ΔR is range resolution of monostatic radar, ΔR_B is range resolution of bistatic radar and B is the signal bandwidth. Range resolution varies according to different illuminator types due to the effect of bandwidth.

2.1.3. Bistatic Radar Equation

As with other radar forms, radar equation can be used to test the suitability of expected performance while designing bistatic radars [11,28,30]. Basic form of the radar equation for a radar with one transmitter can be written as in Equation 2.6 [11,30].

$$\frac{P_R}{P_N} = \frac{P_T G_T}{4\pi R_T^2} \sigma_B \frac{1}{4\pi R_R^2} \frac{G_R \lambda^2}{4\pi} \frac{1}{kT_0 BWF} L_o \tag{2.6}$$

Where;

P_R = received signal power,

P_N = receiver noise power,

P_T = transmitted power,

G_T = transmitter antenna gain,

R_T = transmitter to target range,

σ_B = target bistatic radar cross-section,

R_R = target to receiver range,

G_R = receiver antenna gain,

λ = signal wavelength,

k = Boltzmann's constant,

T_0 = 290K, noise reference temperature,

BW = receiver effective bandwidth,

F = receiver effective noise figure,

L_o = system losses.

When converted to this simple form of the equation by adding pattern propogation factors (F_T, F_R), system losses (L_T, L_R), T_S (receiving system noise temperature) and B_N (receiver noise bandwidth), the SNR (signal to noise ratio), which is one of the important criteria for evaluating system performance, is obtained as in Equations 2.7.

$$SNR = \frac{P_T G_T G_R \lambda^2 \sigma_B F_T^2 F_R^2}{(4\pi)^3 k T_s B_N L_T L_R R_T^2 R_R^2} \tag{2.7}$$

If we say A to the variables that do not change with the range in Equation 2.7, we get Equation 2.8.

$$SNR = \frac{A}{R_T^2 R_R^2} \tag{2.8}$$

When Equation 2.8 is expressed in the polar coordinate system (r, θ) as in Equation 2.9 and consider its range dependency, it creates Cassini ovals for SNR as shown in Figure 2.4. Each curve represents a fixed SNR value. SNR values of two identical targets on the same oval are equal to each other.

$$SNR = \frac{A}{(r^2 + L^2/4)^2 - r^2 L^2 \cos^2 \theta} \tag{2.9}$$

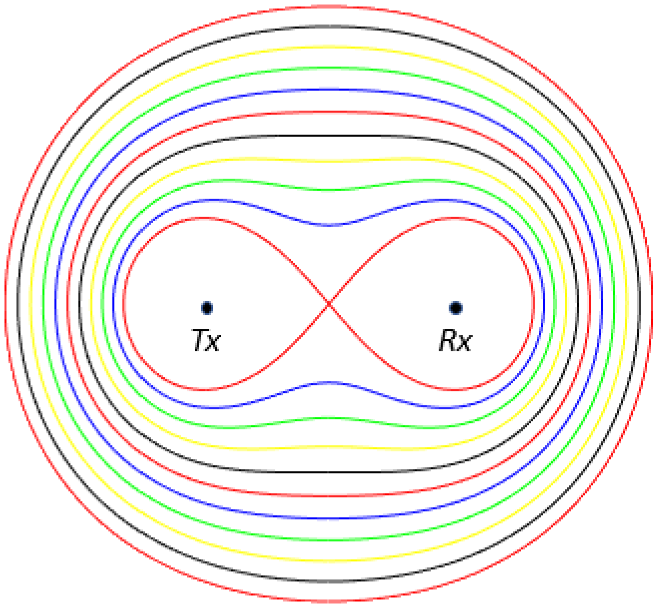


Figure 2.4. Cassini ovals.

2.1.4. Doppler and Ambiguity Function of Bistatic Radar

When a sound source moves towards an observer who is not moving, the observer perceives a louder sound than actually coming from the sound source. This effect is reversed if the sound source is moving away from the observer. The loudness heard by the observer is perceived as less than the sound originating from the sound source. In both cases, a frequency shift occurs. This effect has been discovered by Christian Doppler and is named after him. The bistatic doppler shift can be expressed as in Equation 2.10.

$$f_D = \frac{dR_B}{\lambda dt} \tag{2.10}$$

where λ is the wavelength of the signal. Since the bistatic Doppler shift is directly proportional to the range change, it is affected by the velocity of the receiver, transmitter and target. In accordance with the work presented in this thesis, it is expressed by Equation 2.11 that the transmitter and receiver are in a stationary and fixed position, but the bistatic doppler is formed due to the effect of the velocity vector of the target.

$$f_D = f_T(2\frac{v_T}{c}\cos\delta\cos(\beta/2)) \quad (2.11)$$

where f_T is the carrier frequency, v_T is the velocity of the target, δ is the angle between the target velocity vector and bistatic bisector as mentioned before. Similar to range resolution, the bistatic doppler shift is also affected by the bistatic angle (β). Unlike range resolution, the maximum value of the bistatic Doppler shift is achieved when the velocity vector of the target and the bistatic bisector are in the same direction.

The ambiguity function is a standard way used to evaluating the suitability of the signal for radar purposes by expressing the doppler response and echo delay of the radar system [1,31]. The ambiguity function is expressed in Equation 2.12.

$$X(\tau, f_D) = \int_{-\infty}^{\infty} x(t)x^*(t-\tau)e^{j2\pi f_D t}dt \quad (2.12)$$

where $x(t)$ is the signal and $x(t-\tau)$ is signal with Doppler shift. It is convenient to express time delay τ and Doppler shift f_D in Equation 2.12 in terms of bistatic range R_B and bistatic velocity V, by using substitutions $\tau = R/c$ and $f_D = -V/\lambda$, respectively, where c is the speed of light and λ is the wavelength. Moreover, in practice, the ambiguity function is calculated for finite time, called integration time (T). After these modifications, the ambiguity function can be expressed in the Equation 2.13.

$$X(R_B, V) = \int_{-T/2}^{+T/2} x(t)x^*(t-\frac{R_B}{c})e^{-j2\pi\frac{V}{\lambda}t}dt \quad (2.13)$$

2.2. ILLUMINATORS OF OPPORTUNITY

There are numerous types of currently broadcasting transmitters that can be used for the purpose of passive radar. When choosing the appropriate illuminator type, various properties have to be considered, such as transmitted power, frequency band, signal bandwidth, and modulation according to the purpose of the passive radar system. Commonly used illuminator types for passive radar are mentioned below.

2.2.1. Analog Radio (FM)

FM broadcasting is a technology that uses frequency modulation and was invented by Edwin Howard Armstrong in 1922 to provide high quality sound transmission. FM radio is one of the frequently used and preferred illuminators in passive radar applications [15,18,20,23,26,32,33]. It operates between 88 MHz and 108 MHz frequency range. The transmitter powers can be reach 250 kW, so it provide long detection range or in other words FM signal provide large coverage area. One of the greatest disadvantage of FM radio as a source of illumination for radar, however, is the narrow gap of the signal bandwidth. In addition, the bandwidth of the FM signal changes in time due to the analog modulation applied. The nominal bandwidth of the signal is 150 kHz, with 200 kHz interchannel spacing. However, the instantaneous bandwidth of the signal strongly depends on the content of the used FM channel program. For speech, the bandwidth can be very narrow, which results in degraded range resolution [21,34]. It is available in systems that increase bandwidth by using multiple channels in order to improve the range resolution [17].

2.2.2. Analog TV

Analog television is the original television technology that uses analog signals to transmit video and audio. The television system for each country will specify a number of television channels within the UHF or VHF frequency ranges. A channel actually consists of two signals: the picture information is transmitted using amplitude modulation (AM) on one carrier frequency, and the sound is transmitted with frequency modulation (FM). Signal power varies according to the broadcast made by the channel.

2.2.3. Digital Audio Broadcasting (DAB)

The digital radio standard, DAB (Digital Audio Broadcasting), uses the upper part of the VHF band. It is typically around 200 MHz. The bandwidth of the DAB signal is 1.5 MHz. The transmitted power is low, compared to FM radio, usually in the order of a few kilowatts. The modulation used in the DAB standard is OFDM (Orthogonal Frequency Division Modulation), which is relatively advantageous from the point of view of passive radar. This is because of the (band-limited) noise-like nature of the signal uses OFDM. The main disadvantage of the DAB standard is a smaller area coverage due to few medium or low-powered transmitters. Nonetheless, systems based on DAB transmitters are being constructed, especially in countries where their popularity is relatively high [6].

2.2.4. Digital Video Broadcasting-Terrestrial (DVB-T)

One of the most popular and commonly used standards of digital television signals worldwide is DVB-T (Digital Video Broadcasting-Terrestrial). Recently, it has been preferred as a passive radar illuminator [35-38] due to its worldwide prevalence and advantages [1]. DVB-T is broadcast in the 470–860MHz frequency range. Generally, the power of the transmitters is in the order of tens of kilowatts but occasionally reaching 100 kW. The signal bandwidth is up to 7.61 MHz, which provides very good range resolution. The modulation standard used in DVB-T is OFDM, as in DAB. The modulation itself is relatively advantageous from the point of view of passive radar. However, the signal contains certain elements, such as pilots or cyclic prefix, which have negative effect on the ambiguity function. It is possible to eliminate this effect with appropriate signal processing techniques [39]. Another difficulty which can be encountered when using DVB-T is the use of the SFN (Single Frequency Network) transmission scheme. The scheme consists of transmitting the same signal on the same carrier frequency by different transmitters. This cause a problem which gives rise to ambiguity in the association of target detection to transmitter. Nevertheless, due to its advantages, the DVB-T standard is often used for the purposes of passive radar.

2.2.5. Digital Video Broadcasting-Satellite (DVB-S) TV

DVB-S (Digital Video Broadcast-Satellite) is a standard used for Satellite television broadcasting. Its operating frequency is in the range of 950-2150 MHz. The signal bandwidth is 36 MHz. The power of transmitters can be reach 2 kW. The use of satellite based video broadcast as an illuminator has been frequently used in recent years, especially in studies conducted for the detection of clutter statistics and remnants of natural events on the sea surface [7,40].

2.2.6. Cellular Phone (GSM)

GSM (Global System for Mobile Communications) is the most popular cellular communication standard used all over the world. The system can operate in different frequency bands. The most popular of them are GSM-900 operating around 900 MHz and GSM-1800 operating around 1800 MHz. In more specific explanation, in the case of GSM-900 the uplink frequency range is 890–915 MHz, whereas the downlink frequency range is 935–960 MHz. The frequency bands are divided into 124 channels, each channels are 200 kHz wide. Each frequency channel is further divided into 8 time slots. The physical channel is created by combining the frequency band with a time slot number. The corresponding uplink and downlink channels are separated by 45 MHz. In the case of GSM-1800, the uplink corresponds to 1710–1785 MHz and downlink to 1805–1880 MHz and there are 374 frequency channels. The downlink and uplink channels are separated by 95 MHz.

In general, the GSM-900 is used at longer distances for instance between cities. GSM-1800 is devoted to shorter distances, and is focused on higher data capacity. GSM-900 has more signal power than GSM-1800. The signal power of GSM-900 reaches several hundred, while the signal strength of GSM-1800 does not exceed two digits. In relation to passive radar use, GSM-900 is more suitable for target detection than in GSM-1800 because of transmitter power.

2.2.7. Wireless Fidelity (Wi-Fi)

Wi-Fi (Wireless-Fidelity) is the name of the standards developed by IEEE for the purpose of wireless communication. There are several versions of the standard, under the common name of IEEE 802.11. Most of the versions operate in 2.4 GHz or 5 GHz frequency bands, however, other options are also possible, depending on the IEEE standard's version. In passive radar point of view, bandwidth is sufficient and 16 MHz, trasmitter power is 200mW and its not enough to providing wide coverage.

2.2.8. Comparison Of Different Transmitter Types

In Chapter 2.2, different signal types used as illuminators in passive radar systems are mentioned. These illuminators should be chosen according to the purpose of the system to be used because of their different features that can create advantages and disadvantages. Table 2.2 shows the basic parameters of the different illuminators. The parameter values of the signals may vary depending on the environmental conditions and the broadcast.

Table 2.2. Typical parameters of different transmitter types.

Transmission	**Frequncy Band**	**Bandwidth**	**P_TG_T**
FM	88-108 MHz	200 kHz	250 kW
Analog TV	~550 MHz	5.5 MHz	1 MW
DVB-T	470-860 MHz	7,6 MHz	8-100 kW
DAB	174-240 MHz	1,5 MHz	10 kW
DVB-S	950-2150 MHz	36 MHz	2 kW
GSM (900,1800)	935-960 MHz 1805-1880 MHz	200 kHz	320 W
Wi-Fi	2,4 GHz or 5 GHz	16 MHz	200 mW

When the parameters in Table 2.2 for FM radio signal are examined, having a high value in terms of signal power means a wide coverage area. Due to this feature, it is preferred for passive radar applications. However, having a relatively narrow bandwidth, which varies depending on the content of the broadcast, negatively affects the range resolution.

Although analog TV has good values in terms of basic parameters, it is not widely used for passive radar purposes as it has been replaced by digital video broadcasting in most countries.

DVB-T signal has high values in terms of range resolution due to its wide bandwidth. It is seen that it is suitable for passive radar purposes in terms of signal transmission power. However, the high frequency of the broadcast has a negative effect on the coverage area.

When the DAB signal is evaluated, it has an average bandwidth, so the range resolution also has an average value. The fact that the signal strength is lower than the FM signal puts the FM signal ahead in terms of the width of the coverage area. The same can be seen for broadcast frequency.

It is suitable for short range surveillance applications due to its GSM signal bandwidth and low signal power. Range resolution and coverage are low.

The Wi-Fi signal has a good range resolution due to its high bandwidth. However, the low signal power allows it to be used only in short distance applications.

Due to the low transmission power of the DVB-S signal, the target detection range is short. Due to its high bandwidth, it can be considered as a good illuminator in terms of range resolution.

CHAPTER 3

SIGNAL MODELLING AND ANALYSIS

In this section, the geometry of the designed passive bistatic radar, the signal model detected by the receiver part, the proposed methods for clutter removal and pulse compression part are explained.

3.1. GEOMETRY OF THE DESİGNED PBR SYSTEM

The proposed PBR system includes stationary receiver and transmitter parts. The geometry of the designed system is as in Figure 3.1.

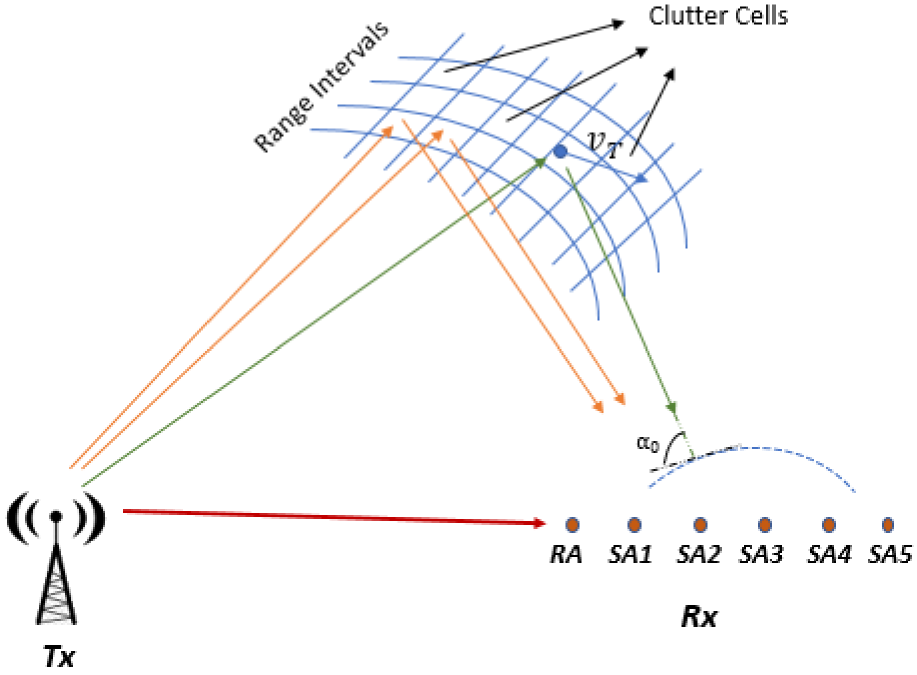


Figure 3.1. Designed system geometry.

The designed system has a PBR geometry in which the transmitter and receiver circuits are in fixed positions. Receiver circuit part consists of 5 antennas with fixed position and distance between antennas $d = 1{,}5$ m. In Chapter 4, the effect on system goals will be shown by changing the number of antennas. One of the antennas on the receiving side is used by the FM illuminator of opportunity to receive the incoming signal directly and is called the reference antenna. The remaining antennas were used to detect the moving target in the vicinity. These antennas also play an important role in the clutter elimination phase.

The working diagram of the designed passive radar is as in Figure 3.2.

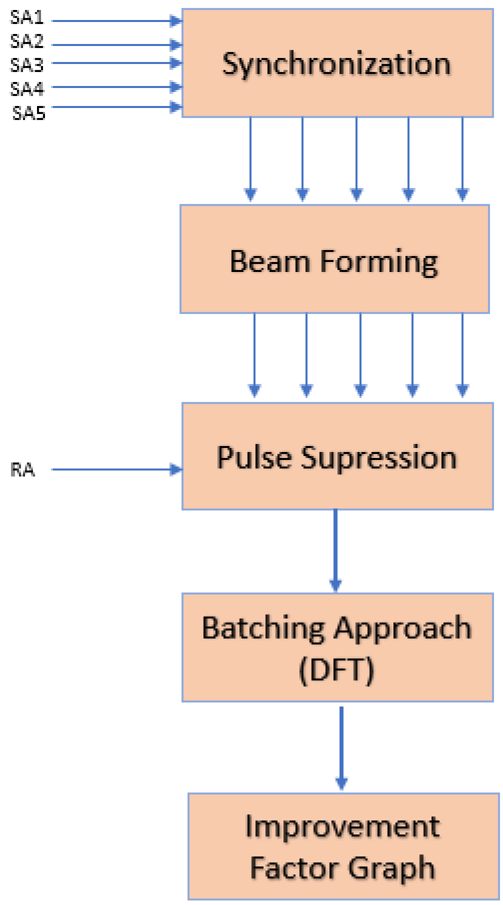


Figure 3.2. Working diagram of the designed PBR.

Reflected signals from both the target and the clutter are obtained by the antennas SA1, SA2, SA3, SA4, which are used for surveillance purposes. After the synchronization between the antennas, the signals are digitized. The digitized signals are compressed and optimized by means of a matched filter. The clutter signal obtained from constant environmental factors is suppressed by beamforming. The doppler frequency parts where the suppressed clutter signal is present and target detection can be made are indicated by the improvement factor.

3.2. TRANSMITTED SIGNAL MODEL

The signal received by the surveillance antennas is as in Equation 3.1.

$$x^{(n)}(t) = x_C^{(n)}(t) + x_T^{(n)}(t) + x_N^{(n)}(t) \tag{3.1}$$

The signal obtained by the designed system consists of the sum of $x_C^{(n)}(t)$, $x_T^{(n)}(t)$, $x_N^{(n)}(t)$ signals. The signal originating from clutter represented by $x_C^{(n)}(t)$, $x_T^{(n)}(t)$ is the echo signal reflected from the target and $x_N^{(n)}(t)$ is the noise signal. n represents the surveillance antennas SA1, SA2, SA3, SA4 and SA5.

3.2.1. Clutter Signal

The clutter signal is formed by the reflection of the transmitted signal by stationary objects such as a house and skyscraper on the ground. The resulting signal reduces the target detection performance of the passive bistatic radar. The signal reflected from a single scatterer for each surveillance antenna is as in Equation 3.2.

$$\begin{aligned}
x_0^{(SA1)}(t) &= A_0 s(t-\tau_0) \\
x_0^{(SA2)}(t) &= A_0 s(t-\tau_0) e^{j2\pi\frac{d}{\lambda}\cos\alpha_0} \\
x_0^{(SA3)}(t) &= A_0 s(t-\tau_0) e^{j2\pi\frac{2d}{\lambda}\cos\alpha_0} \\
x_0^{(SA4)}(t) &= A_0 s(t-\tau_0) e^{j2\pi\frac{3d}{\lambda}\cos\alpha_0} \\
x_0^{(SA5)}(t) &= A_0 s(t-\tau_0) e^{j2\pi\frac{4d}{\lambda}\cos\alpha_0}
\end{aligned} \tag{3.2}$$

In Equation 3.2, A_0 is the complex amplitude, time t, and $s(t)$ denotes the signal emitted from the transmitter. τ_0 is the bistatic propagation delay and is calculated by equation 3.3.

$$\tau_0 = \frac{R_T + R_R - L}{c} \tag{3.3}$$

Equation 3.4 is obtained when the $x_0^{(SA1)}(t)$, $x_0^{(SA2)}(t)$, $x_0^{(SA3)}(t)$, $x_0^{(SA4)}(t)$, $x_0^{(SA5)}(t)$ signals received by the surveillance antennas are sampled with the sampling frequency F_s.

$$\begin{aligned} x_0^{(SA1)}[l] &= A_0 s\left[l - l_{\tau_0}\right] \\ x_0^{(SA2)}[l] &= A_0 s\left[l - l_{\tau_0}\right] e^{j2\pi\frac{d}{\lambda}\cos\alpha_0} \\ x_0^{(SA3)}[l] &= A_0 s\left[l - l_{\tau_0}\right] e^{j2\pi\frac{2d}{\lambda}\cos\alpha_0} \\ x_0^{(SA4)}[l] &= A_0 s\left[l - l_{\tau_0}\right] e^{j2\pi\frac{3d}{\lambda}\cos\alpha_0} \\ x_0^{(SA5)}[l] &= A_0 s[l - l_{\tau_0}] e^{j2\pi\frac{4d}{\lambda}\cos\alpha_0} \end{aligned} \tag{3.4}$$

l and l_{τ_0} are expressed by Equation 3.5 and Equation 3.6, respectively.

$$l = tF_s \tag{3.5}$$

$$l_{\tau_0} = \tau_0 F_s \tag{3.6}$$

The reference and surveillance signals synchronized by the receiving system, respectively, are divided into data parts, and related to the batching approach, the surveillance signal part is cross-linked to the reference part. Range/Doppler map is obtained by applying DFT (Discrete Fourier Transform) to the obtained matrix. In Equation 3.7, $s(t)$ is expressed by the result of the batching approach. The total time of sampling is called the CPI (Coherent Processing Interval).

$$s(t) = \sum_{b=0}^{B-1} s_b(t - bT) \tag{3.7}$$

where B is the number of pieces in a CPI and T is the duration of a piece.

When it is assumed that a CPI consists of a total of B parts, the signals received from the surveillance antennas are expressed by Equation 3.8.

$$
\begin{aligned}
x_0^{(SA1)}[l,b] &= A_0 \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] \\
x_0^{(SA2)}[l,b] &= A_0 \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi \frac{d}{\lambda}\cos\alpha_0} \\
x_0^{(SA3)}[l,b] &= A_0 \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi \frac{2d}{\lambda}\cos\alpha_0} \\
x_0^{(SA4)}[l,b] &= A_0 \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi \frac{3d}{\lambda}\cos\alpha_0} \\
x_0^{(SA5)}[l,b] &= A_0 \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi \frac{4d}{\lambda}\cos\alpha_0}
\end{aligned}
\tag{3.8}
$$

where L_N is the number of samples in a piece, which is obtained by equation 3.9.

$$L_N = TF_s \tag{3.9}$$

The surveillance antennas receive signals from multiple ranges. It must be taken into account that different angular spacings (ϕ_r) come from different angles of incidence (α). In addition, considering that the amplitudes are modeled with the Rayleigh distribution ($A_r(\alpha)$), $x_c(t)$ is expressed by the equation 3.10.

$$
\begin{aligned}
x_c^{(SA1)}[l,b] &= \sum_{r=1}^{R} \int_{\phi_r} A_r(\alpha) \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] d\alpha \\
x_c^{(SA2)}[l,b] &= \sum_{r=1}^{R} \int_{\phi_r} A_r(\alpha) \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi \frac{d}{\lambda}\cos\alpha_0} d\alpha
\end{aligned}
\tag{3.10}
$$

$$x_c^{(SA3)}[l,b] = \sum_{r=1}^{R} \int_{\phi_r} A_r(\alpha) \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi\frac{2d}{\lambda}\cos\alpha_0}\, d\alpha$$
$$x_c^{(SA4)}[l,b] = \sum_{r=1}^{R} \int_{\phi_r} A_r(\alpha) \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi\frac{3d}{\lambda}\cos\alpha_0}\, d\alpha$$
$$x_c^{(SA5)}[l,b] = \sum_{r=1}^{R} \int_{\phi_r} A_r(\alpha) \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi\frac{4d}{\lambda}\cos\alpha_0}\, d\alpha$$

3.2.2. Target Signal

In addition to the clutter signals from the surveillance antennas of the passive radar, the echo signal reflected from the target is also received. In the designed scenario, it is assumed that there is a target in the observation environment. In such a case, there will be no effect from other cells to the range range where the target is located. Since the target is in motion, the target's Doppler is calculated in Equation 2.11. The target signal $x_T^{(n)}(t)$ received from the surveillance antennas is obtained by combining Equation 2.11 and Equation 3.8 as in Equation 3.11.

$$\begin{aligned}
x_T^{(SA1)} &= A_0 \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi f_T\left(2\frac{v_T}{c}\cos\delta\,\cos\beta/2\right)bT} \\
x_T^{(SA2)} &= A_0 \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi f_T(2\frac{v_T}{c}\cos\delta\,\cos\beta/2)bT} e^{j2\pi\frac{d}{\lambda}\cos\alpha_0} \\
x_T^{(SA3)} &= A_0 \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi f_T\left(2\frac{v_T}{c}\cos\delta\,\cos\beta/2\right)bT} e^{j2\pi\frac{2d}{\lambda}\cos\alpha_0} \\
x_T^{(SA4)} &= A_0 \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi f_T\left(2\frac{v_T}{c}\cos\delta\,\cos\beta/2\right)bT} e^{j2\pi\frac{3d}{\lambda}\cos\alpha_0} \\
x_T^{(SA5)} &= A_0 \sum_{b=0}^{B-1} s_b\left[l - bL_N - l_{\tau_0}\right] e^{j2\pi f_T(2\frac{v_T}{c}\cos\delta\,\cos\beta/2)bT} e^{j2\pi\frac{4d}{\lambda}\cos\alpha_0}
\end{aligned} \tag{3.11}$$

3.2.3. Noise Signal

Noise is the unwanted signals encountered in most electronic applications that occur randomly and statistically. Noise signals can come from the antenna to the receiving system or from the receiver's own circuits. The noise component $x_N^{(n)}(t)$ is modeled with AWGN (Additive White Gaussian Noise). AWGN is a basic noise model used in information theory to simulate the effect of many random processes occurring in nature. This noise is frequently used in radar, sonar, communication and signal processing applications. The sample noises generated for the surveillance antennas are shown in Figure 3.3.

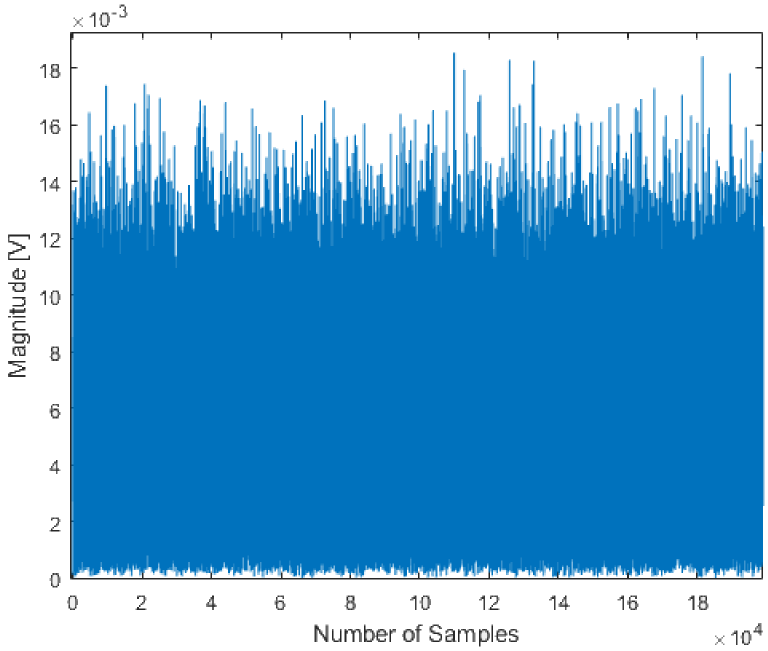


Figure 3.3. Surveillence antennas AWGN.

3.3. CLUTTER CANCELLATION

The passive radar system designed consists of fixed position receiver and transmitter parts. For this reason, stationary targets are located at 0 Hz in the Doppler space. Since stationary targets with Doppler frequency of 0 Hz express clutter, clutter removal was performed with a beamforming approach using a matched filter in the pulse suppression stage. The results obtained by the proposed methods are shown in section 4.

3.3.1. Beamforming

Beamforming is a digital technique that focuses the radar transmitter and receiver in a particular direction [22,41]. The side to side direction is commonly referred to as the azimuth and the up and down direction as the elevation. Beamforming can be used to focus the radar over both azimuth and elevations.

In the receive beamformer the signal from each antenna may be amplified by a different "weight." Different weighting patterns can be used to achieve the desired sensitivity patterns. A main lobe is produced together with nulls and sidelobes. As well as controlling the main lobe width (beamwidth) and the sidelobe levels, the position of a null can be controlled. This is useful to ignore noise or jammers in one particular direction, while listening for events in other directions. A similar result can be obtained on transmission.

Each antenna element must have a delay, or phase adjustment, such that after this adjustment, all elements will have a common phase of the signal. If the angle $\alpha_0 = 0$, then all the elements will receive the signal simultaneously, and no phase adjustment is necessary. At a non-zero angle, each element will have a delay to provide alignment of the wavefront across the antenna array. Figure 3.4 shows the schematic representation of the proposed digital beamforming approach in the system.

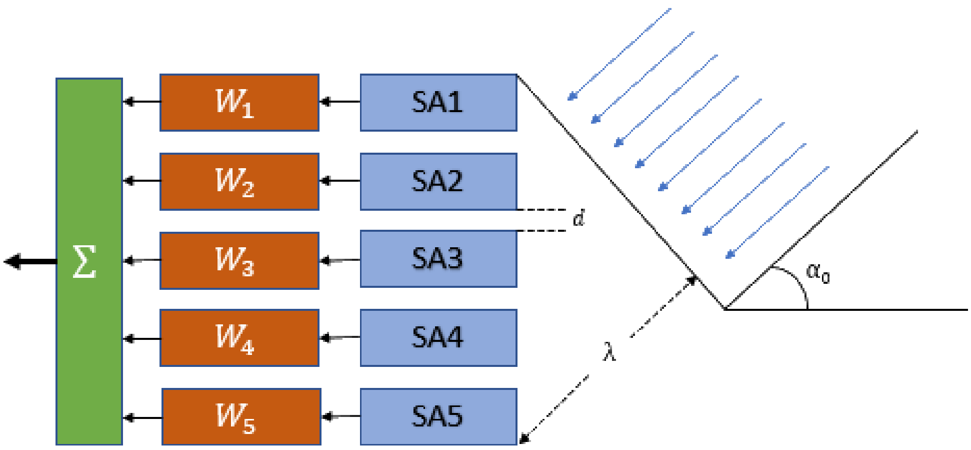


Figure 3.4. Digital beamforming schematic.

Once each antenna element input is downconverted to baseband by a common clock and local oscillator, each antenna input is delayed by the correct amount so that the wave front arriving from a given direction is aligned. This delay can be digitally implemented by phase rotations, or multiplication by $W_i = e^{j\alpha_0} i$. For better side lobe control, the amplitude can also be varied, by using $W_i = A_i e^{j\alpha_0} i$. By adaptively changing W_i for each antenna input, the beamforming can be accomplished. In the proposed PBR system, the selectivity determined by the angle of incidence in the receiver antennas by means of beamforming plays an important role in clutter removal and target detection. The phase shift can be express as Equation 3.12.

$$\alpha_n = \frac{2\pi}{\lambda} d(n-1) \sin \alpha_0 \tag{3.12}$$

Then the steering vector can be calculated as Equation 3.13.

$$a_n(\alpha_0) = e^{j\alpha_n} \tag{3.13}$$

Beamforming coefficient vector (W_n) express as Equation 3.14. ϕ_0 is represents the particular direction. If $\phi_0 = 0$ the beamforming coefficient vector $W_n = 1$.

$$W_n = e^{j\frac{2\pi d}{\lambda}(n-1)} \sin(\phi_0) \tag{3.14}$$

Then the radiation pattern of the receiver antennas can be express as Equation 3.15

$$F_R(\alpha_0, W) = \sum_{n=1}^{N} W_n^* a_n(\alpha_0) = \frac{\sin(N\frac{\pi d}{\lambda}\sin\alpha_0)}{\sin(\frac{\pi d}{\lambda}\sin\alpha_0)} e^{j\frac{\pi d}{\lambda}(N-1)} \tag{3.15}$$

3.3.2. Pulse Suppression

Active radar systems can control the signal transmitted to the receiver, since the transmitted signal is under the control of its own transmitter. However, passive radars do not have their own transmitting system, unlike active radars, so the waveform of the received signal must be changed. Matching filter is used to change the waveform of the signal and make it suitable.

The state of the received signal after pulse suppression is given in Equation 3.16.

$$\begin{aligned} d^{(a)}[l,b] &= r^{(a)}[l,b] * h[l,b] \qquad\qquad b = 0, \dots, B-1 \\ &= IDFT\{DFT\{r^{(a)}[l,b]\} \odot DFT\{h[l,b]\}\} \end{aligned} \tag{3.16}$$

where $*$ corresponds to convolution and $\odot$ to element-based multiplication. $d^{(a)}[l,b]$ contains the pulse suppression version of each part of the signal. DFT represents discrete fourier transform and IDFT rapresents the inverse version of DFT.

3.3.3. Match Filter

Matched filters are a basic tool in electrical engineering for extracting known wavelets from a signal that has been contaminated by noise [42]. In this section, the matched filter used in the pulse compression phase is explained.

In signal processing, a matched filter is obtained by correlating a known delayed signal, or template, with an unknown signal to detect the presence of the template in the unknown transmitted signal. Matched filters are commonly used in radar, in which a known signal is sent out, and the reflected signal is examined for common elements of the transmitted signal. Pulse compression is an example of matched filtering.

The unknown shape of the echo signals in passive bistatic radar is a main problem. The echo signals from the target and the disturbance take different forms with the addition of the Doppler effects. Moreover, the echo signal may even overlap with multiple Doppler frequencies. For example, both the Doppler frequencies of the rotor blades and the Doppler frequencies of the fuselage, as well as the radial velocity of the entire helicopter, are important in recognizing a helicopter. In practice, there must be a special matched filter for each Doppler frequency spectrum.

The pulse compression is a radar specific form of the matched filter. This filter is most suitable if the received signal is the same as the sent signal. Here, the beamforming process applied to the signal comes into play. When used in conjunction with a compatible filter, the signal can be optimized for effective clutter cancellation and target detection.

CHAPTER 4

SIMULATION RESULTS AND DISCUSSION

The simulation of the PBR system based on the use of an FM radio transmitter as an illuminator was made using the MATLAB program. The simulation parameters are given in Chapter 4.1. A matched filter is used for pulse compression.

In Chapter 4.2, the response of the designed 5 antenna system with beamforming and clutter removal at different CNR values is shown. The results obtained are compared to show the effects of CNR on clutter cancellation. The proposed beamforming approach is evaluated by comparing the effect of CNR value on clutter and target detection capability.

The response of the passive radar system designed in Chapter 4.3 is shown when four antennas, three surveillance and one reference, are used. Simulation results are given for different CNR values. The proposed beamforming approach is evaluated by comparing the effect of CNR value on clutter and target detection capability.

In Chapter 4.4, the number of receiving antennas is reduced to three and tested for different CNR values. The proposed beamforming approach is evaluated by comparing the effect of different antenna numbers on clutter and target detection capability.

4.1. SIMULATION PARAMETERS

The carrier frequency (f_T) of the received FM signal is 100 MHz. Therefore, the wavelength becomes 3 m from $\lambda = c/f_T$. The angular spacing is in the range 0 to π. The range interval number (R) is set to 100. The received signal was sampled with a sampling frequency (F_S) of 200 kHz. A CPI consists of a total of 100 parts. The duration (T) of each part is 0.5 ms. The distance between the surveillance antennas (d) is 1.5 m. The number of surveillance antennas (n) was changed to 3, 4 and 5 to observe its effect on the improvement factor. The CNR value was tested at different values such as 30, 40 and 50 dB, and its effect on clutter suppression was examined. All system parameters are given in Table 4.1.

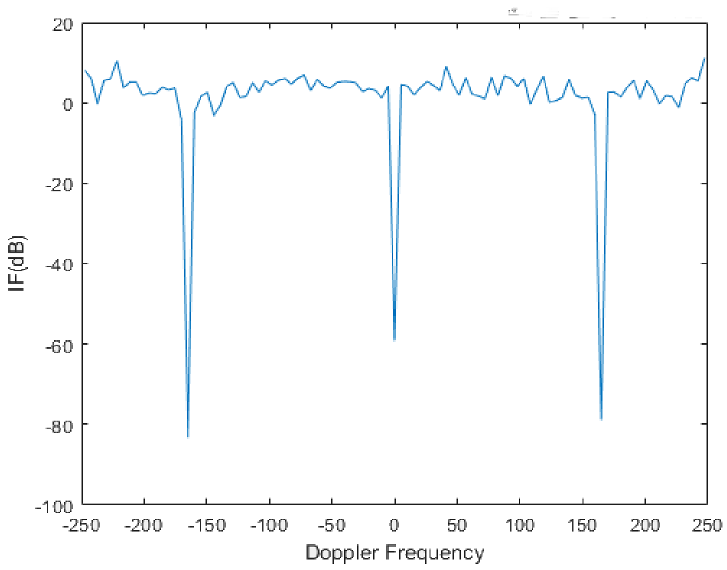
Table 4.1. Simulation parameters and values of parameters.

Symbol	**Parameter**	**Values**
f_T	Carrier frequency	100 MHz
λ	Wavelength	3 m
R	Range interval number	100
ϕ_r	Angular spacing	[0, π]
F_s	Sampling frequency	200 kHz
d	Distance between surveillance antennas	1,5 m
CNR	Clutter to noise ratio	30-40-50 dB
B	Number of batches in CPI	100
L	Number of sample in one batch	400
T	Duration of one batch	0,5 ms
n	Number of surveillance antennas	3-4-5

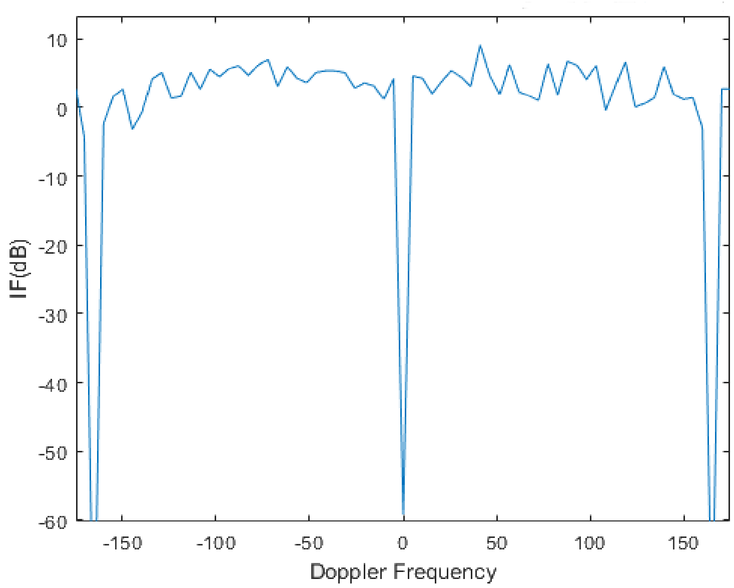
The improvement factor (IF) is an important evaluation criteria in PBR [43]. IF is the beneficial sign and clutter sign ratio at the output of the filter (here: Moving Target Echo/Stationary Target Echo) divided by the beneficial sign and noise sign ratio at the input of this filter, averaging over the desired target velocities. This definition covers not only the attenuation of fixed target echoes, but also the gain of Doppler frequency smeared fixed target echoes. In this section, the clutter cancellation and target detection capability of the PBR system is evaluated over IF. The effect of range resolution on IF should not be overlooked.

4.2. PBR SYSTEM WITH FIVE ANTENNAS

In this section, the improvement factor of the proposed five antenna PBR system is given for different CNR values. The response of the system for 30 CNR values is shown in Figure 4.1a and in Figure 4.1b zoomed in between 15 dB and -60 dB.



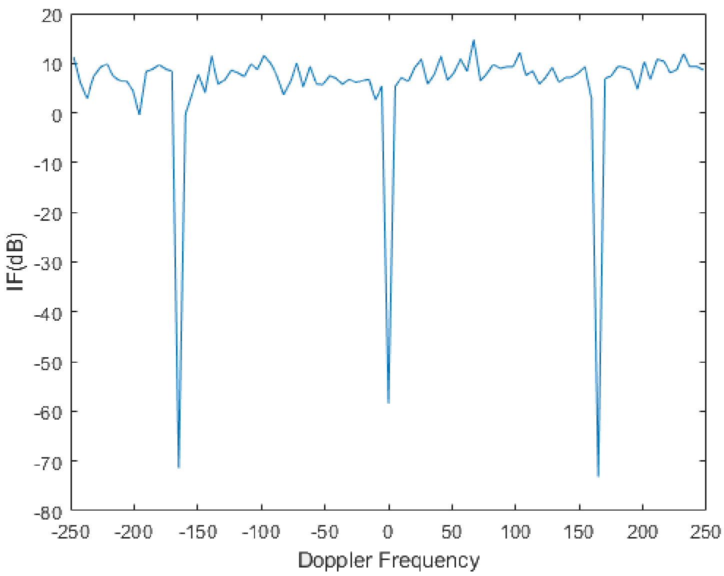
(a)



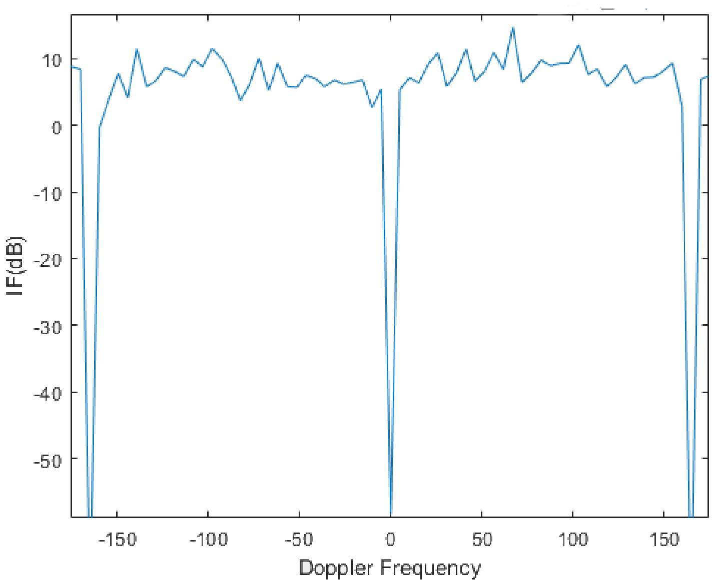
(b)

Figure 4.1. IF of PBR system with CNR 30 and five receiver antennas. a) simulation results, b) zoomed version of the results.

The Improvement Factor (IF) graph where the CNR value is 40 in the proposed PBR system with 5 antenna receivers is given in Figure 4.2a and zoomed version of it given in Figure 4.2b. The fact that the clutter rate has been increased is seen with the differences in the parts containing the moving targets, as the Doppler frequency is different from zero.



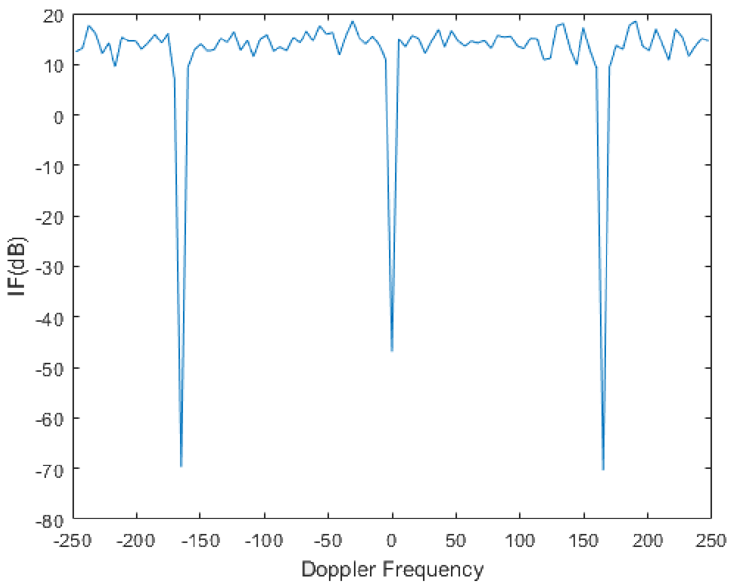
(a)



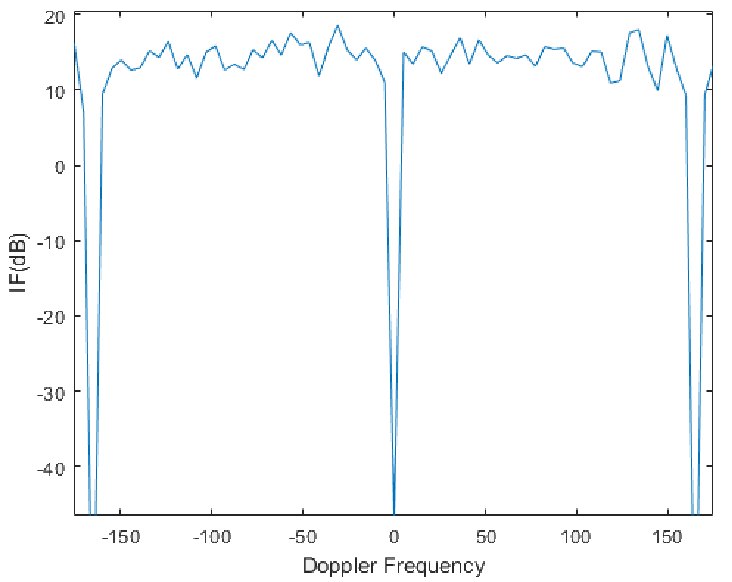
(b)

Figure 4.2. IF of PBR system with CNR 40 and five receiver antennas. a) simulation results, b) zoomed version of the results.

The response of the system for 50 CNR values is shown in Figure 4.3a and in Figure 4.3b zoomed in between 20 dB and -45 dB.



(a)



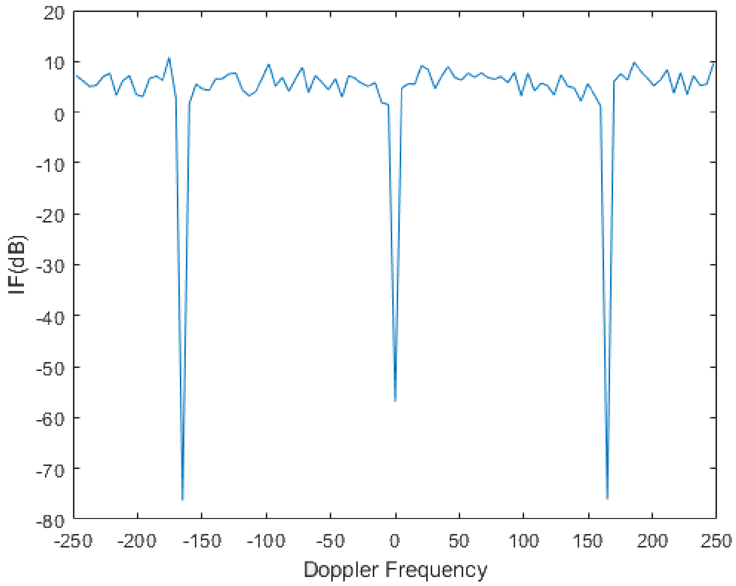
(b)

Figure 4.3. IF of PBR system with CNR 50 and five receiver antennas. a) simulation results, b) zoomed version of the results.

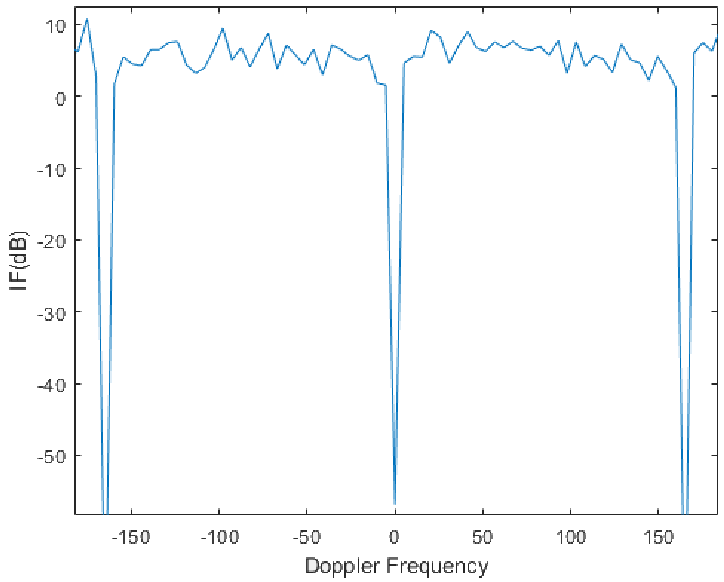
When the Improvement Factor (IF) of the system is considered in the parts where the Doppler frequency is zero, it is seen that the clutter is effectively suppressed. For various CNR values, different IF values were obtained for clutter cancellation. The IF value, which is -60 dB at 30 CNR, decreases below -60 dB at 40 CNR and below -50 dB at 50 CNR. The ratio of the clutter signal to the received signal affects the system performance negatively. Within three CNR values, the system is suitable for target detection.

4.3. PBR SYSTEM WITH FOUR ANTENNAS

In this section, the improvement factor of the proposed four antenna PBR system is given for different CNR values. The response of the system for 30 CNR values is shown in Figure 4.4a and in Figure 4.4b zoomed in between 12 dB and -58 dB.



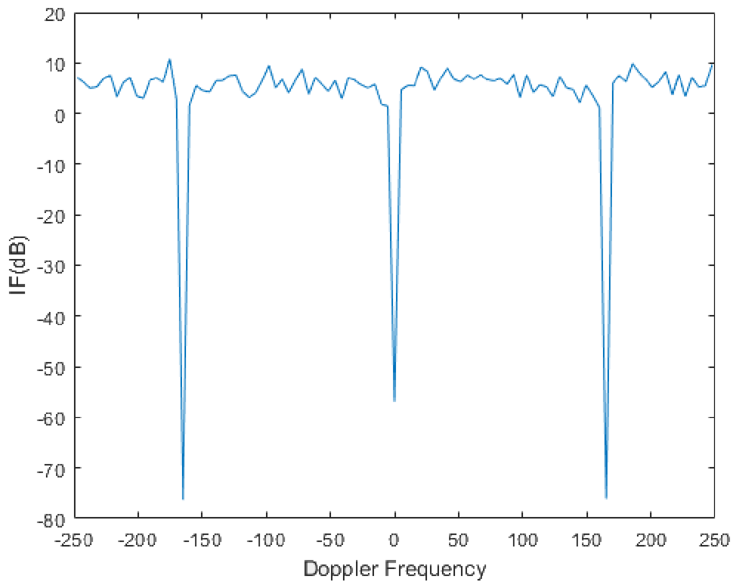
(a)



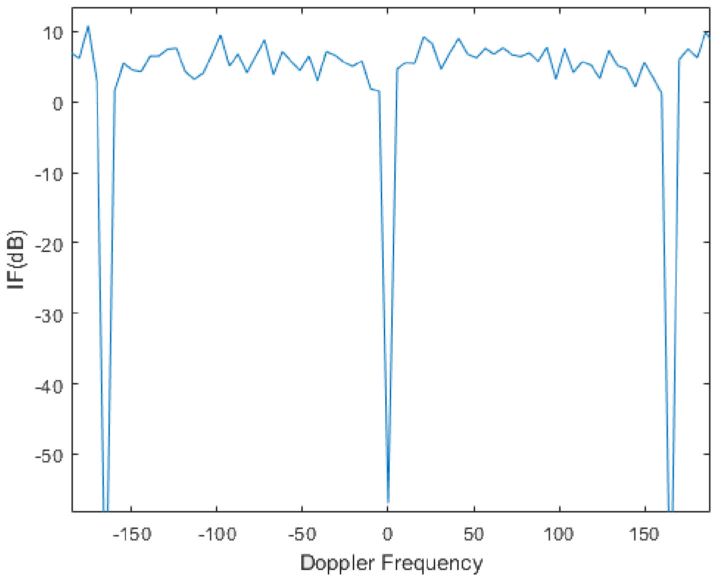
(b)

Figure 4.4. IF of PBR system with CNR 30 and four receiver antennas. a) simulation results, b) zoomed version of the results.

The response of the system for 40 CNR values is shown in Figure 4.5a and in Figure 4.5b zoomed in between 12 dB and -58 dB. For various CNR values, different IF values were obtained for clutter cancellation. The IF value, which is about -55 dB at 30 CNR.



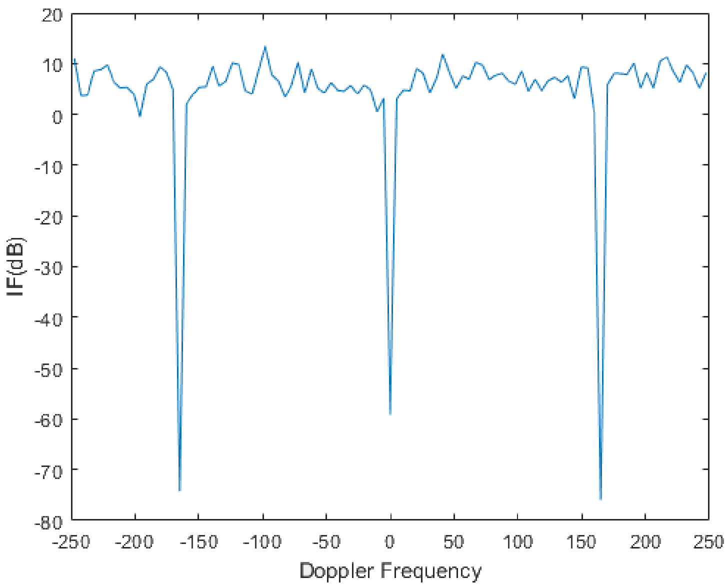
(a)



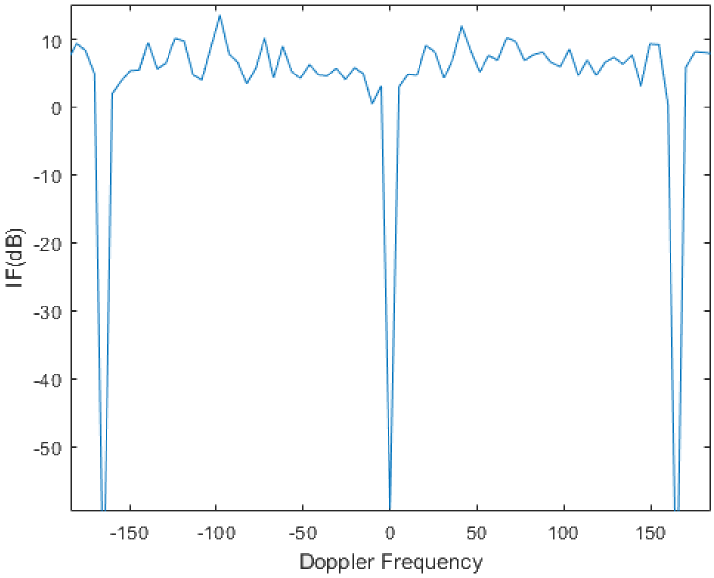
(b)

Figure 4.5. IF of PBR system with CNR 40 and four receiver antennas. a) simulation results, b) zoomed version of the results.

The response of the system for 50 CNR values is shown in Figure 4.6a and in Figure 4.6b zoomed in between 15 dB and -58 dB. IF value not changing much at 40 CNR. IF is the same as the other CNR values at 50 CNR. Differences are observed in target detection parts.



(a)

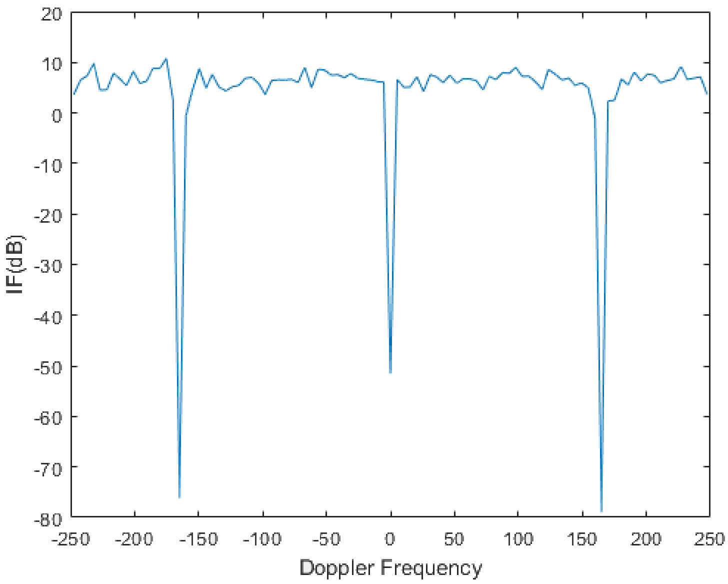


(b)

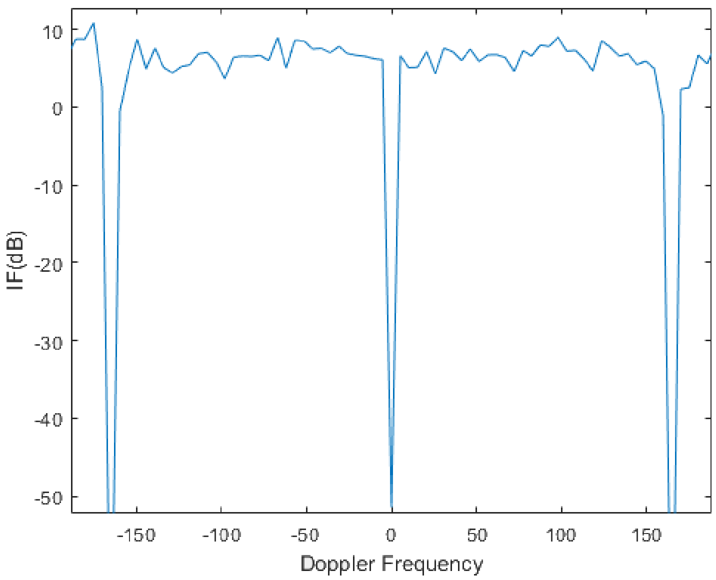
Figure 4.6. IF of PBR system with CNR 50 and four receiver antennas. a) simulation results, b) zoomed version of the results.

4.4. PBR SYSTEM WITH THREE ANTENNAS

In this section, the improvement factor of the proposed three antenna PBR system is given for different CNR values. The response of the system for 30 CNR values is shown in Figure 4.7a and in Figure 4.7b zoomed in between 13 dB and -52 dB.



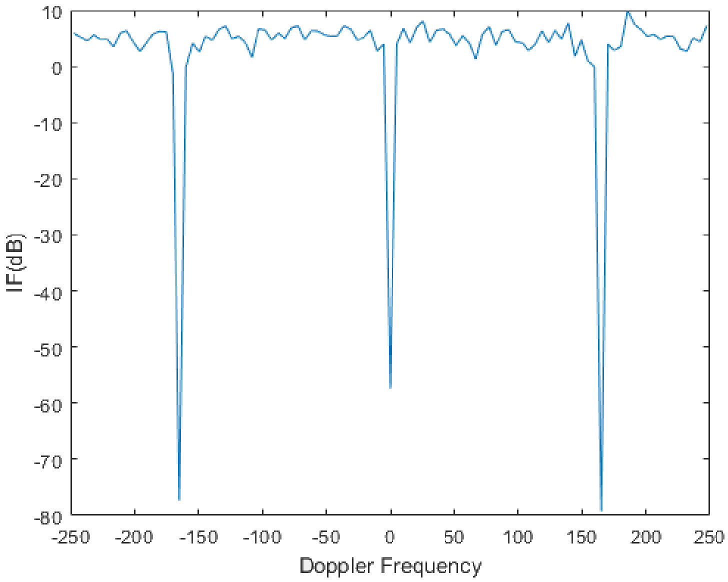
(a)



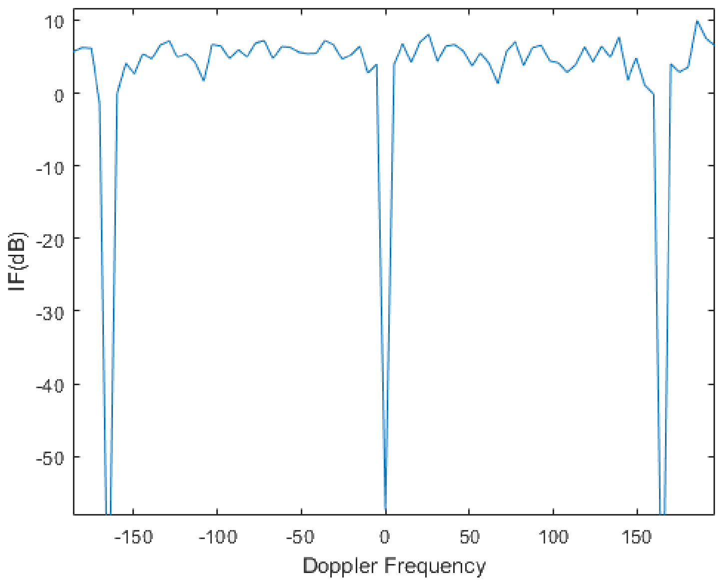
(b)

Figure 4.7. IF of PBR system with CNR 30 and three receiver antennas. a) simulation results, b) zoomed version of the results.

The response of the system for 40 CNR values is shown in Figure 4.6a and in Figure 4.6b zoomed in between 12 dB and -57 dB.



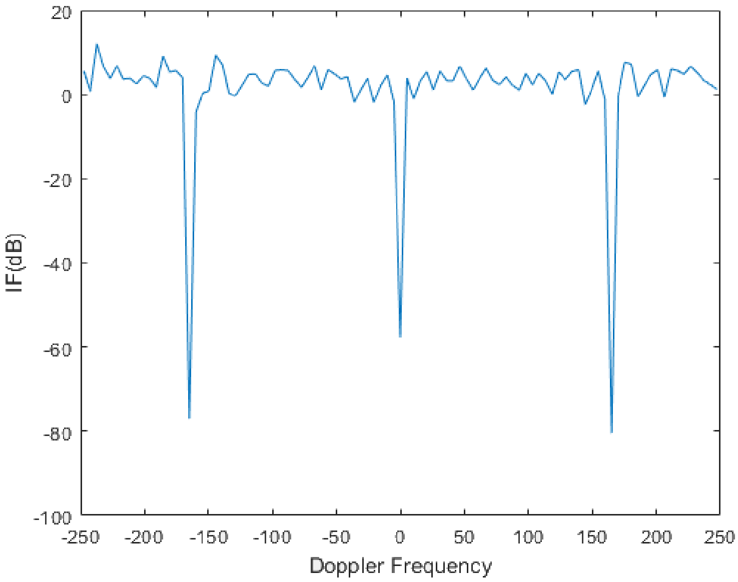
(a)



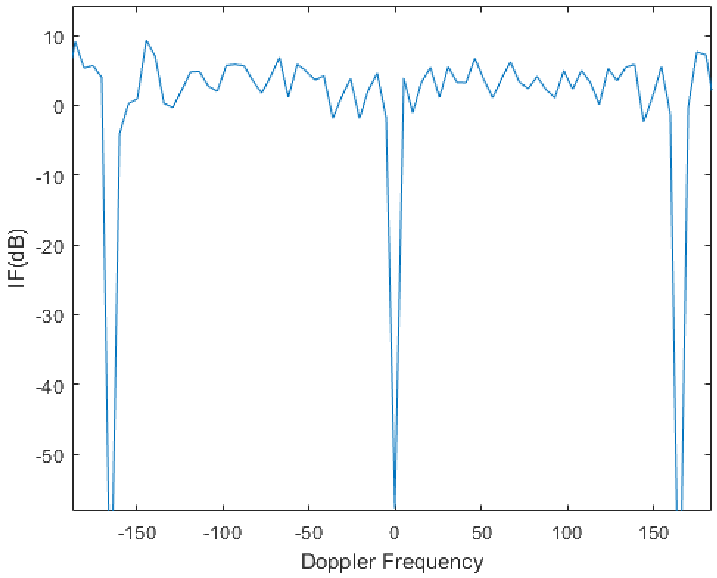
(b)

Figure 4.8. IF of PBR system with CNR 40 and three receiver antennas. a) simulation results, b) zoomed version of the results.

The response of the system for 50 CNR values is shown in Figure 4.6a and in Figure 4.6b zoomed in between 14 dB and -57 dB.



(a)



(b)

Figure 4.9. IF of PBR system with CNR 50 and three receiver antennas. a) simulation results, b) zoomed version of the results.

The results obtained with different CNR values and antenna numbers show that the proposed system performance decreases at high clutter level. In terms of target detection and riot suppression, the effects are given in the outputs. The beamforming method used is more effective in terms of clutter suppression when the number of antennas increases. It is seen that the target detection capability of the system, which is arranged using three antennas, has decreased. Especially in Figure 4.9, where the CNR value is high, the IF outputs show how much the target detection capability is compared to the five-antenna and four-antenna system. Correspondingly, the gain does not rise above 10 dB and shows an unstable response.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

In this study, the suitability of passive bistatic radar system with fixed receiver and transmitter circuits for clutter suppression and target detection has been analyzed. In this context, primarily the clutter signal, target signal and noise signal are modeled. The clutter and target signals are modeled by considering parameters such as scatterers, different angles of incidence, and distances between antennas. The noise signal is modeled using AWGN. The clutter signal, which affects the target detection performance of the passive radar, is suppressed by applying beamforming. A matched filter is used in the pulse compression stage. The methods used were tested for different CNR values and antenna numbers. Clutter is suppressed in the signal portions containing fixed targets where the Doppler frequency is 0 Hz. The parts containing the moving target, where the Doppler frequency is different from zero, are made suitable for target detection by obtaining gain.

5.1. FUTURE WORKS

This section covers future work on passive radar.

- Examining the situations that result from different broadcasts of different channels and affect the system performance.
- Testing of passive radar system on non-stationary platforms.
- Examining the effects of DSI (Direct Signal Interference), DPI (Direct Path Interference) and MPI (Multipath Interference).
- Increasing the range resolution by increasing the number of simultaneous channels used. Here, the increased complexity of processing should be taken into account.

- Increasing target detection capability or obtaining more precise results by using passive radar structure in a multistatic geometry.
- Examining the changes caused by the effects of different illuminators on the system.
- Modeling different landforms such as the sea and their effects on clutter suppression.

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RESUME

İbrahim Ethem YILMAZ graduated first and elementary education in Ordu and Sakarya, respectively. He completed high school education in V.B. Zübeyde Hanım High School, after that, he started undergraduate program in Yıldız Technical University Department of Electronic and Communication Engineering in 2014. Then he was begin the M. Sc. education in Karabuk University in 2020. Then in 2021, he started assignment as a Research Assistant in Karabük University Department of Electric-Electronic Engineering.