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**LOCALIZED OPTIMIZATION AND EFFECTIVENESS
ANALYSIS OF MEDIUM PRF AIRBORNE PULSE
DOPPLER RADARS IN THE TURKISH AIR FORCE**

by

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September 2011

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MEDIUM PRF AIRBORNE PULSE DOPPLER RADARS IN THE TURKISH AIR
FORCE**

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ABSTRACT

The use of different pulse repetition frequencies (PRFs) delivers significantly different behaviors to airborne radars. For instance, the main purpose for using low PRF is to obtain an unambiguous range measurement. However, the tradeoff when using a low PRF is that the measurement of the target's radial velocity is highly ambiguous and can result in missing some target detections. On the other hand, high PRF is used to reduce or eliminate ambiguities in the measurement of radial velocity. A high PRF, however, causes a highly ambiguous range measurement. The true range is resolved by transmitting multiple waveforms with different PRFs.

A modified form of pulse Doppler radar that operates at a medium PRF has both range and Doppler shift ambiguities. However, medium PRF is potentially better for detecting aircraft with low closing speeds than high PRF pulse Doppler.

This thesis will focus on the effectiveness and localized optimization of medium PRF in airborne pulse Doppler radars, for the Turkish Air Force. This thesis will also present an analysis of medium PRF performance in a low altitude, air-to-air operating environment offering moderate range radar capability and also delivering acceptable range and Doppler resolution within that operating environment.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADT	Automatic Detection and Tracking
CW	Continuous Wave
EM	Electromagnetic
FM-CW	Frequency Modulated Continuous Wave
HF	High Frequency
IEEE	Institute of Electrical and Electronics Engineers
ISAR	Inverse Synthetic Aperture Radar
ITU	International Telecommunications Union
LOS	Line of Sight
MLC	Mainlobe Clutter
MPRF	Medium Pulse Repetition Frequency
MTI	Moving Target Indication
OTH	Over-the-Horizon
PRF	Pulse Repetition Frequency
SAM	Surface-to-Air Missiles
SAR	Synthetic Aperture Radar
SCR	Signal-to-Clutter Ratio
SLAR	Side-Looking Airborne Radar
SLC	Sidelobe Clutter
STT	Single Target Tracker
TWS	Track-While-Scan

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I. INTRODUCTION

Radar, which stands for “RADio Detection and Ranging,” involves an electromagnetic sensor which is used to detect and locate targets and has a major role in modern weapon systems. The key features of radar are long-range detection capability and all weather functionality. Basically, radar propagates electromagnetic energy from an antenna to targets. The energy then reflects and scatters in various directions, some of which returns back to the radar antenna. This radar backscatter is often called an “echo.” After a process of amplification and signal processing, presence of a target is detected by the radar together with potential descriptive information about the target [1].

Modern technology presents us different types of radars varying in size, shape and features depending on the intended targets and purpose. There are radars which are designed for early warning and have detection capabilities that extend over hundreds of miles, whereas smaller types of radars are used in some sport games in order to measure the speed of the ball. Most of the radars relevant to this thesis fall somewhere between these two extremes.

With respect to military applications, we can classify radars into three groups: Land-based radars, naval radars and airborne radars. Land-based radar systems in the field vary in size and purpose as well as in complexity. The most common land-based radars are “mortar and artillery location radar, artillery fire control radar, short-to-long range air surveillance radar, and surface-to-air missile (SAM) target and illumination radar” [2]. The radars commonly used in naval applications vary widely, including “air surveillance, surface search, surface-to-air, and surface-to surface weapon control and target acquisition radar” [2]. Airborne radars have a more comprehensive variety of fielded systems when compared with land-based and naval radars. The major challenge in airborne applications is the limited space and weight due to the platform and the complexity caused by the need of multi-functionality. These multiple functions include “target location and weapon delivery, navigation, terrain following and avoidance, weather detection, missile detection and warning, altimetry, and surface mapping” [2] many of which are required for the survival of the airborne platform.

The radar design depends on the requirements which it is supposed to meet and the frequencies used in order to accomplish these goals. Radars that have been designed thus far operate at a range of frequencies varying between a few megahertz to almost 300 terahertz. The most common application for the low frequency end is the Over-the-Horizon (OTH) Radars, and for high frequencies the most common application is Laser Radar. The portion of the electromagnetic (EM) spectrum used for radar is depicted in Figure 1 [3].

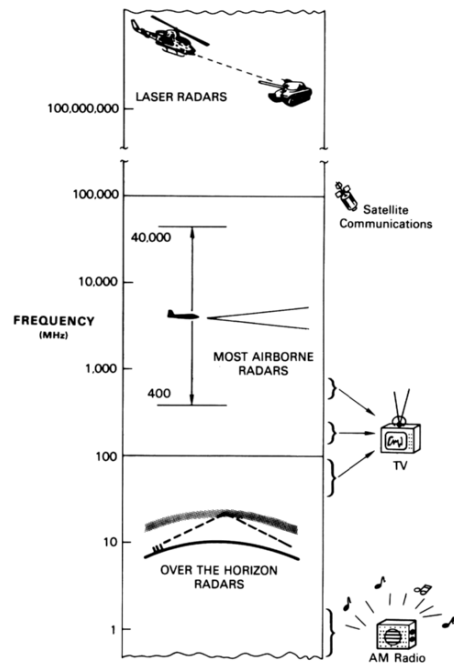


Figure 1. The Use of EM Spectrum for Radar (From [3])

Echoes caused by returns other than the intended target are one of the main issues that radars have to overcome. These echoes, which are called clutter, can occur due to land, weather and sea. The magnitude of clutter echoes can be larger than the target's own echo, making the target undetectable. The best solution for handling clutter is utilizing the Doppler effect. Doppler radars use the Doppler effect by means of measuring the frequency shift between the frequencies that are transmitted from the radar and received from the target in order to enable better target detection [1], [4].

There are two types of Doppler radars: Continuous wave and pulse Doppler radars. This thesis will focus more on pulse Doppler radars with regard to the identified

area of research (i.e., medium PRF systems). Pulse Doppler radars are categorized in three different pulse repetition frequency (PRF) groups: low PRF, medium PRF and high PRF.

Depending on the unambiguous range equation [Eq. (1.1)], where f_r is the PRF in Hz and c is the speed of light, the maximum range which low PRF radars can handle is inside the first part of the range zones. The performance range of the low PRF radar is ambiguous for returns beyond this point [3].

$$R_u = \frac{c}{2f_r} \quad (1.1)$$

The opposite condition holds for high PRF Doppler radars as this range limit moves closer to the radar and targets are now generally ambiguous. The Doppler frequency resolution of these two radars is just the opposite of the described range ambiguity (i.e., Doppler radar is generally unambiguous for high PRF radar systems and ambiguous for low PRF radar designs) [3].

Medium PRF Doppler radar is a compromise design which is recognized as ambiguous both in the range and Doppler domains. The main advantage of medium PRF radar is that it has better performance than low PRF radars against closing targets and better performance than high PRF radars against tail-aspect targets. This feature makes medium PRF radars uniquely suitable where all aspect coverage is needed [5].

The selection of pulse repetition frequencies has significance since the determination of the presence and the extent of ambiguity in both the range and Doppler domains depends on the selection. Range ambiguities occur if the interpulse period, T , which is inversely proportional to the pulse repetition frequency [Eq. (1.2)], is shorter than the return time of the echoes of the preceding pulse. In other words, the radar is unable to determine which echo belongs to which pulse. If the second pulse is transmitted before the echo of the first returns to radar, then the target will show up at a shorter distance than it really is (Figure 2). Therefore, there are more range ambiguities for high PRF radars since the interpulse periods are shorter [3].

$$T = \frac{1}{f_r} \quad (1.2)$$

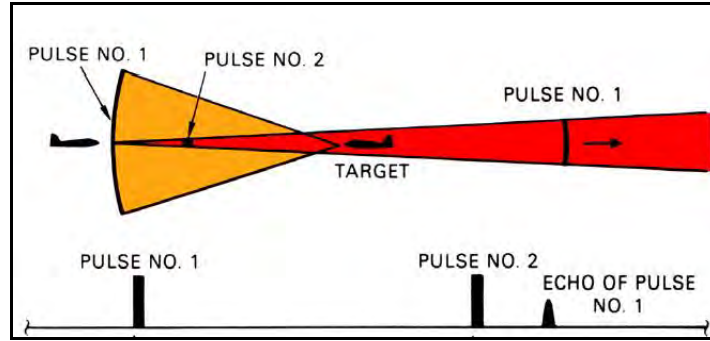


Figure 2. Occurrence of Range Ambiguity (From [3])

Pulsed systems have transmit spectrums consisting of spectral lines that are separated by the PRF. If the PRF is higher than the highest Doppler frequency, it is assumed that any spectral line to which a Doppler filter is tuned may be the next lower line of the transmitted signal shifted by the target's Doppler frequency. Otherwise, there will be Doppler ambiguities. In this case, lower PRFs have more ambiguity due to narrow spaced spectral lines [3], [6]. The ambiguities in both range and Doppler domains for all PRF categories are shown in Table 1.

PRF	RANGE	DOPPLER
HIGH	AMBIGUOUS	UNAMBIGUOUS
MEDIUM	AMBIGUOUS	AMBIGUOUS
LOW	UNAMBIGUOUS	AMBIGUOUS

Table 1. PRF Categories (From [3])

A. AREA OF RESEARCH

This thesis examines the performance and the localized optimization of medium PRF in airborne pulse Doppler radars in the Turkish Air Force.

Pulse Doppler radars use the measurement of Doppler frequency shift in order to differentiate echoes and reject clutter to acquire target detection. Airborne pulse Doppler radars use multiple PRFs for different purposes. However, every PRF selection presents a performance tradeoff. The main purpose of using a low PRF is to determine an

unambiguous range, but the tradeoff is highly ambiguous target radial velocity that can be interpreted through Doppler frequency and can cause some target detection failures. In contrast, high PRF radar provides unambiguous radial velocity (Doppler), whereas it has inherent ambiguous range measurement limitations as a tradeoff.

Medium PRF, which has the desired features of both low and high PRFs, has a better performance in detection of targets that have low closing speeds. Although a medium PRF radar has both range and Doppler ambiguities, it uses multiple PRFs in order to overcome ambiguous target information [4], [7].

This thesis focuses on the use of medium PRF in airborne pulse Doppler radars, its effectiveness analysis and the localized optimization for the Turkish Air Force. The thesis also presents an analysis performance in a simulated theater of operation involving low altitude, air-to-air medium range radar capability and an acceptable range and Doppler resolution within that environment.

Although this thesis utilizes numerous resources, the references shown in Table 2 have the most significant contributions to the related areas. The complete list is provided in List of References.

Author	Book	Related Area
Merrill Skolnik	Radar Handbook, 3 rd Ed.	Radar Systems
Guy Morris Linda Harkness	Airborne Pulsed Doppler Radar, 2 nd Ed.	Airborne Radar
George W. Stimson	Introduction to Airborne Radar, 2 nd Ed.	Airborne Radar

Table 2. Major Resources

B. MAJOR RESEARCH QUESTIONS

This study addresses the following questions:

1. Primary Question

- a.** How can the Turkish Air Force optimally use medium PRF in airborne pulse Doppler radars?

2. Subsidiary Questions

- a.** What are the existing systems that use medium PRF?
- b.** What are the advantages/limitations of medium PRF in time and frequency domains?
- c.** How can we optimally model the time and frequency domain behaviors of medium PRF?
- d.** How do we optimize a medium PRF system for use in Turkey?

C. BENEFITS OF THE STUDY

The results of this thesis will provide useful information to the Turkish Air Force about the radar systems in its current inventory that use medium PRF and their characteristics in specified environments, as well as optimal ways to use them for future system designs.

D. CHAPTER OUTLINE

This thesis is composed of five chapters. Chapter I provides an introduction to radars and gives brief information about pulse repetition frequency categories.

Chapter II presents information about radar fundamentals. The Doppler effect is examined and its use in pulse radars is explained. Detailed information about the three pulse repetition frequency categories is presented. Some of the existing airborne pulse Doppler radar systems which employ medium pulse repetition frequency (MPRF) are examined.

Chapter III discusses the characteristics of MPRF. The range and the Doppler profiles of MPRF, together with its clutter rejection capabilities and range- Doppler blind zones are examined. The advantages and the limitations of MPRF are presented.

Chapter IV explains the procedures of the developed MPRF performance evaluation simulation. First, the ambiguity function is explained and the initial phase of the simulation is presented, where MPRF is evaluated in nonclutter environment. After that information about clutter is presented, followed by the second phase of the simulation. The same procedures are then repeated for a clutter environment scenario. This chapter ends with brief discussion on optimization and the last phase of the simulation, where a local optimum multiple MPRF sequence is sought.

Chapter V is the conclusion. The results obtained from the simulation are explained. Recommendations are given for future studies.

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II. DOPPLER RADAR

A. RADAR FUNDAMENTALS

Radars use EM energy in order to detect and locate objects such as aircraft, ships, etc. The operating principles are simple. Radar propagates EM energy with its antenna. This radiated energy hits the objects and the possible targets in the environment. The intercepted energy reflects and scatters in various directions. Some portion of this energy returns to the radar, indicating the presence of objects (Figure 3). In order to acquire target information such as range, velocity, altitude, etc., the received signal is compared with the known transmitted signal [8].

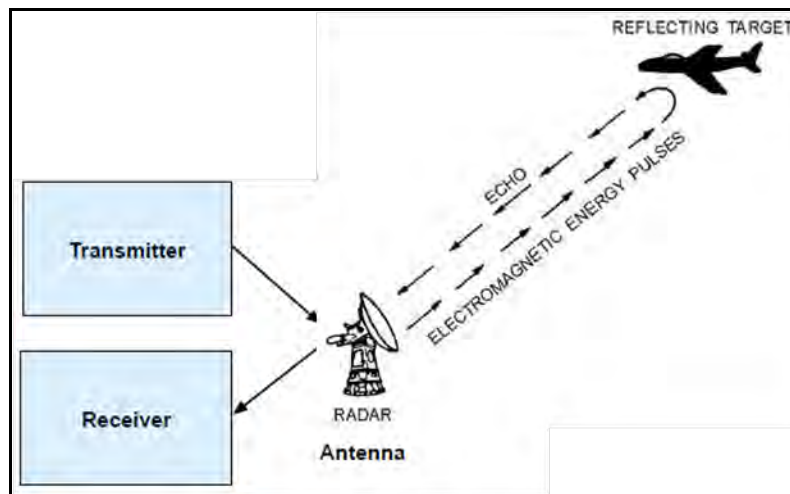


Figure 3. Radar Echo (After [9])

Radar, in its simplest form, consists of a transmitter and a receiver, two antennas and a display unit. After the transmitter propagates a radio wave, the reflected signal from the target in the direction of the radar is received by the antenna and a return is indicated on the display unit showing the location of the target. Technological developments have made it possible to use a single antenna for both transmitting and receiving in a configuration described as monostatic [3].

The radar waveform usually used to detect targets is called a “pulse” (Figure 4). The receiver remains in stand-by mode as the transmitter is operating in order to avoid

receiver interference. The receiver turns on as soon as the transmission is complete and listens for the echoes. Radar uses several pulses in order to discriminate multiple targets at various directions and distances. “The rate at which the pulses are transmitted is called pulse repetition frequency” [3], and identified as PRF.

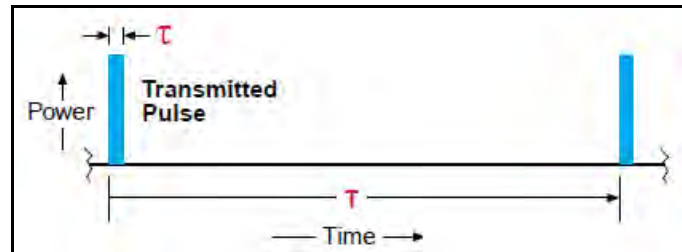


Figure 4. Radio Waveform in Pulses (From [3])

In order for radar to detect a target within the microwave frequencies used by most current systems, line of sight (LOS) visibility between radar and target is required whereas lower frequency HF systems that allow target detection beyond the visual horizon are the generally accepted exception. Another requirement is that the target echo must be strong enough to be detected when compared to the output noise of the receiver including the natural clutter that also enters the receiver antenna. Target range is a highly important factor that defines the strength of the target echo as it has the inverse ratio of $1/R^4$ due to the two-way propagation of the received signal (Figure 5) [3]. For radar pulse acquisition systems with limited dynamic range (difference between the largest and smallest detectable signals), the strong range attenuation characteristic significantly influences the performance range (or reach) of a radar system.

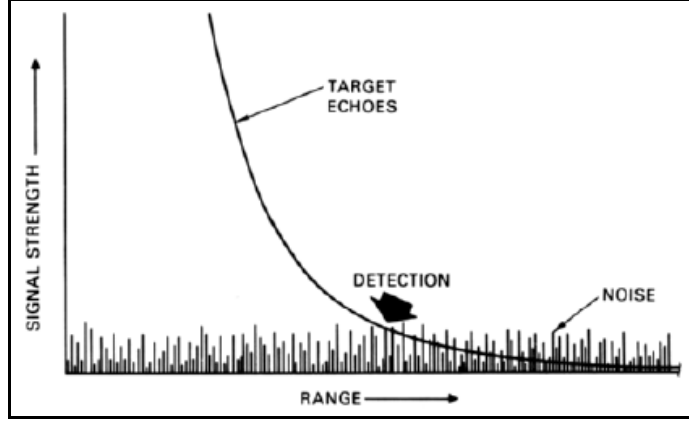


Figure 5. Signal Strength Vs. Target Range (From [3])

1. Radar Equation

The radar range equation is very useful for showing the relationship between the range of the radar and other radar characteristics. It also presents a basic understanding of the radar performance depending on these factors [1], [8]. The simple form of the radar equation is shown in Eq. (2.1).

$$P_r = \frac{P_t G_t}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \times A_e \quad (2.1)$$

The first part at the right hand side of the equation is the power density at a distance R that radiates the power P_t using an antenna with a directed gain of G_t . The second part includes the radar cross section of the target, σ , viewed as a power density source that radiates echoes back to the radar. The incident power density at the radar using the left and middle terms of Eq. (2.1) are shown in Eq. (2.2).

$$\text{Reradiated power density back at the radar} = \frac{P_t G_t}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \quad (2.2)$$

The last term in the simple form of the radar range equation describes the collection capability of the radar receiver. The echo power returned from the target to the radar is received by the receiving antenna, which has an effective area of A_e .

The maximum range of the radar, R_{max} , is the limit where beyond the target can no longer be detected and it is assumed that at this distance the received signal power,

P_r , is exactly equal to the minimum detectable signal, S_{min} . Rewriting Eq. (2.1), the maximum range of the radar is shown in Eq. (2.3).

$$R_{max} = \left[\frac{P_t G_t A_e \sigma}{(4\pi)^2 S_{min}} \right]^{\frac{1}{4}} \quad (2.3)$$

Considering radars usually use the same antenna both for transmitting and receiving, the maximum range equation can also be written as below using Eq. (2.4) and Eq. (2.5) where λ is wavelength, c is velocity of propagation and f is frequency [1], [8].

$$\lambda = \frac{c}{f} \quad (2.4)$$

$$G_t = G_r = G = \frac{4\pi A_e}{\lambda^2} \quad (2.5)$$

$$R_{max} = \left[\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 S_{min}} \right]^{\frac{1}{4}} \quad (2.6)$$

$$R_{max} = \left[\frac{P_t A_e^2 \sigma}{4\pi \lambda^2 S_{min}} \right]^{\frac{1}{4}} \quad (2.7)$$

2. Radar Frequencies

Each radar has its own operation range within the frequency spectrum, depending on its design purposes. Furthermore, since radars are widely used in the military, the exact frequency ranges are often not revealed.

The IEEE has approved a standard radar frequency letter band nomenclature for convenience in order to show the regions of the spectrum that radars use. These designations depend on the frequency allocations assigned by the International Telecommunications Union (ITU) [1], [8], [10].

This study focuses on X-band (8–12 GHz) and S-band (2–4 GHz) with regard to the area of research. The complete designations are shown in Appendix A.

a. The Significance of Radar Frequency on Performance

The design frequency of a radar is related to the performance objectives that are to be accomplished. However, every frequency selection has its own trade-offs.

Physical size of the radar is one of these trade-offs. The size and the weight of the hardware grow as the frequency decreases due to the wavelength increase. In contrast, radars that use higher frequencies can fit in much smaller spaces, and they can be much lighter in weight.

The choice of frequency also affects the transmitted power. Physically large radars, which use low frequencies and long wavelengths, can transmit more energy depending on the voltage potential per unit of length.

Another frequency-relevant consideration for radar performance is the beamwidth. Beamwidth is the width of the mainlobe. Azimuth beamwidth and elevation beamwidth are commonly used as the shape of the beam is not generally symmetrical. It is described as the angle between the nulls on each side of the mainlobe, but for radar systems, it is common to use the beamwidth where the maximum power decreases by half, called the “3 dB Beamwidth” as -3 in decibels corresponds to half power (Figure 6) [3].

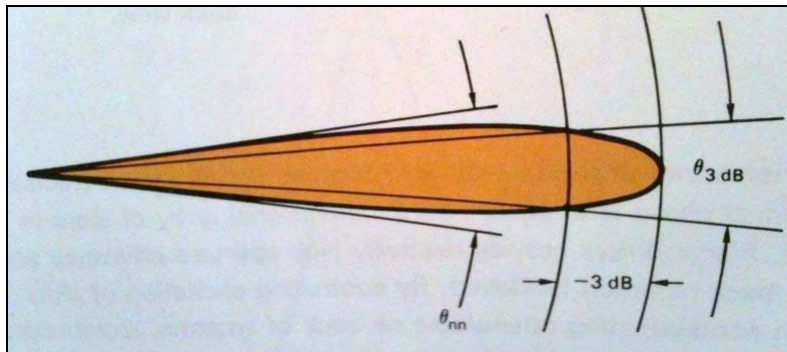


Figure 6. Null-to-Null and 3dB Beamwidths (From [3])

Beamwidth depends on the size of the antenna aperture, the dimensions of which are expressed in wavelengths as shown in Figure 7. The beam gets narrower as the dimensions of antenna aperture gets larger in wavelengths. If the illumination is uniformly distributed over a linear array or rectangular aperture, the null-to-null bandwidth in the far field is then expressed in radians as in Eq. (2.8). Null-to-null beamwidth for a linear array is twice the angle between the boresight line and the first null, which is also equal to twice the ratio of wavelength to length of the array (Figure 8)

for uniform antenna illumination. The 3 dB beamwidths for a linear array and circular aperture with diameter d in radians are shown in Eq. (2.9) and Eq. (2.10), respectively.

$$\theta_{nn} = 2 \frac{\lambda}{L} \quad (2.8)$$

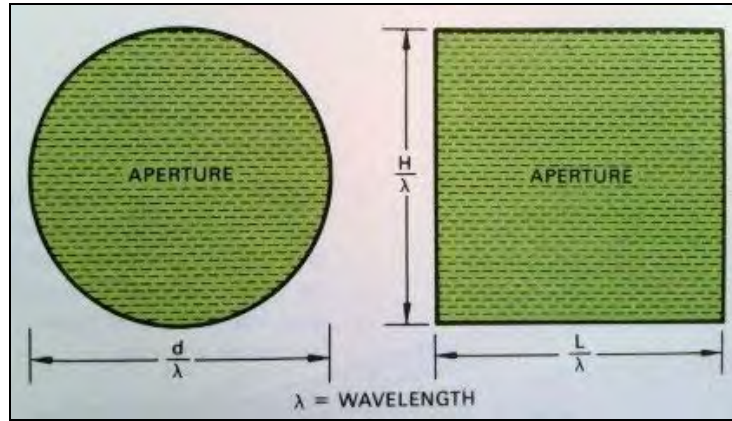


Figure 7. Dimensions of Antenna Aperture (From [3])

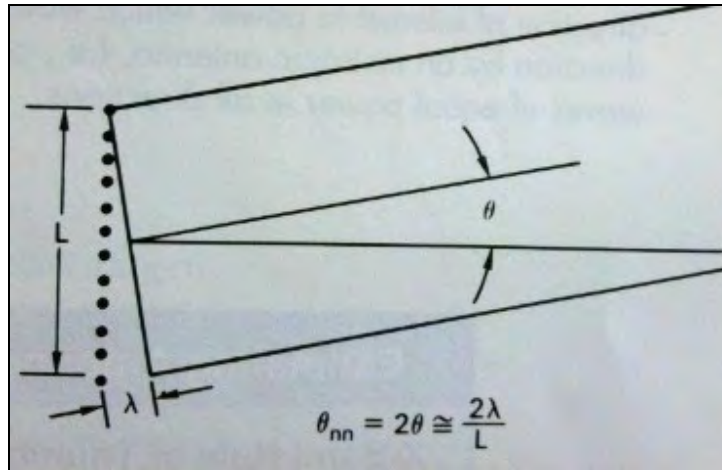


Figure 8. Null-to-Null Beamwidth for a Linear Array (From [3])

$$\theta_{3dB} = 0.88 \frac{\lambda}{L} \quad (2.9)$$

$$\theta_{3dB} = 1.02 \frac{\lambda}{d} \quad (2.10)$$

Sidelobes of an antenna exist not only forward but in all directions, including behind the antenna (i.e., rear direction). The strongest sidelobes are those

closest to the mainlobe. Since the sidelobes cover a large solid angle, approximately one-fourth of the total radiated power is not within the mainlobe. From a military operations perspective, sidelobes can create vulnerabilities to jamming, they can collect undesired multipath returns (clutter) and they also increase the probability of detection of the radar by adversaries. Therefore, it is usually desirable to reduce the gain of the first sidelobes significantly below the mainlobe (i.e., 80 dB). In order to increase solid angle efficiency, which is the concentration of the radiated power in the mainlobe, sidelobes are to be reduced and the sidelobe power redirected to the mainlobe for increasing the antenna gain. In addition, sidelobe reduction also diminishes the problems related to jamming and ground clutter. If the antenna is designed to radiate more power through the center of the aperture than the parts near the edge of the aperture, where sidelobes are produced, then the far field sidelobes are minimized. This is called “Illumination Tapering” and although desirable from a sidelobe level perspective, tapering increases beamwidth and also reduces the peak gain of the mainlobe (Figure 9). For an antenna using tapered illumination, which is commonly used in fighter aircraft radars, the 3 dB beamwidth in radians is shown in Eq. (2.11) [3].

$$\theta_{3dB} = 1.25 \frac{\lambda}{d} \quad (2.11)$$

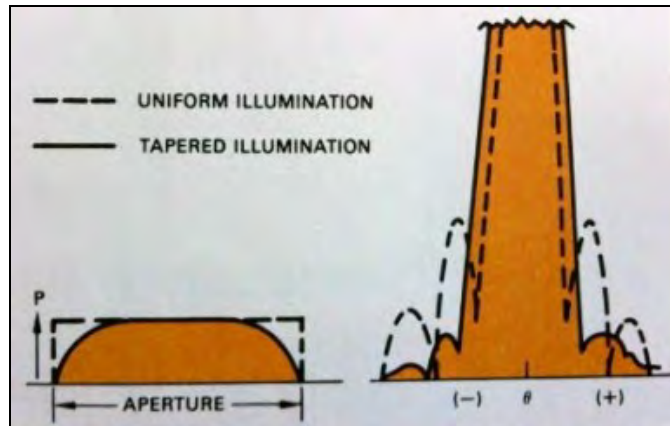


Figure 9. Tapered Illumination (From [3])

As previously stated, the beamwidth of a radar antenna depends on the wavelength and the physical size of the antenna. In order to obtain narrow beams when using low frequencies, large antennas must be used, whereas small antennas are adequate

for high frequencies. The narrowness of the beamwidth provides more concentrated power in a specified direction (i.e., directivity or gain) and better angular resolution [3].

Atmospheric attenuation is another factor that affects the performance of a radar. Electromagnetic energy is attenuated in the atmosphere due to absorption and scattering. When the frequency of the radar is close to or exactly at the resonant frequencies of water vapor and oxygen, the energy of the radar is attenuated [8]. An estimate for the amount of attenuation in dB/km with regard to frequency is shown in Figure 10.

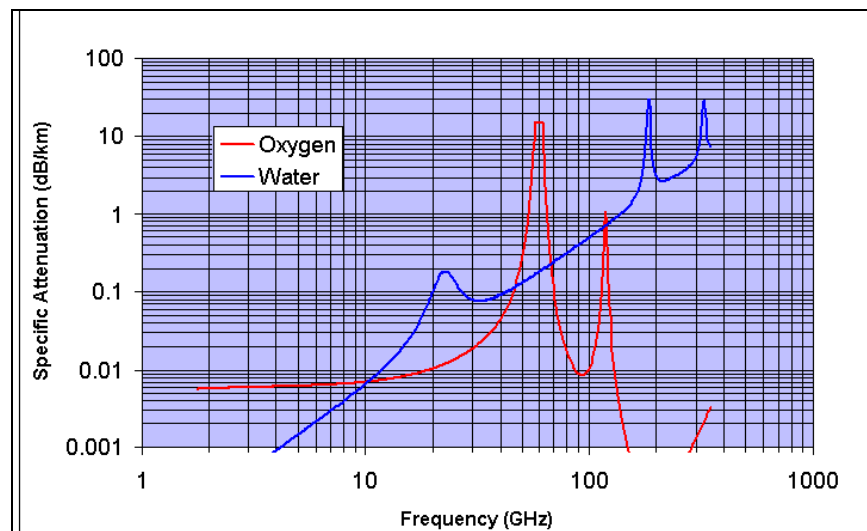


Figure 10. Atmospheric Attenuation (After [11])

The blue curve in Figure 10 represents the absorption related to water vapor in the atmosphere and the red curve represents the absorption due to oxygen. The resonance peaks of water vapor occur at 22.2 GHz and 184 GHz. The resonance peaks of oxygen occur at 60 GHz and 118 GHz. Atmospheric attenuation starts to strongly affect the performance of a radar approximately for frequencies above 10 GHz. The curves shown in Figure 10 are only approximate values of attenuation because altitude affects atmospheric attenuation as the number of the molecules that can absorb radar energy is reduced at higher altitudes [3], [8].

Ambient noise, which includes the electrical noise caused by other sources and atmospheric noise, is also detrimental to the performance of radars. Electrical noise decreases with frequency whereas atmospheric noise increases with frequency.

Last, but not least, Doppler shift is a consideration for radar system performance. As the frequency increases, Doppler shift within a closing target gets greater and excessive amounts of Doppler shift may cause some limitations with regard to the frequency to be used in a radar [3]. Doppler will be described later in this thesis.

3. Types of Radar

Radars can be classified by many aspects with regard to their performance, physical, or functional features. Some of the more generally accepted classifications are shown below [1]. Of those listed, this thesis will focus in the area of pulse Doppler radar.

- Pulse radar
- High-resolution radar
- Pulse compression radar
- Continuous Wave (CW) radar
- Frequency Modulated CW (FM-CW) radar
- Surveillance radar
- Moving Target Indication (MTI)
- Pulse Doppler radar
- Tracking radar:
 - Single Target Tracker (STT)
 - Automatic Detection and Tracking (ADT)
 - Track-While-Scan (TWS)
 - Phased array tracker
- Imaging radar
- Side-Looking Airborne Radar (SLAR)
- Synthetic Aperture Radar (SAR)
- Inverse Synthetic Aperture Radar (ISAR)
- Weapon control radar

- Guidance radar
- Weather (meteorological) observation
- Doppler weather radar
- Target recognition
- Multifunction radar

B. DOPPLER RADAR

1. Doppler Effect

“The Doppler effect is a shift in the carrier frequency of a wave radiated, reflected, or received by an object in motion” [3]. When a radiation source propagates a wave, the wave is compressed as the motion continues. The direction of the compression is the same as the motion causing wave compression. Meanwhile, the wave spreads out in directions opposite to the motion (Figure 11) [3].

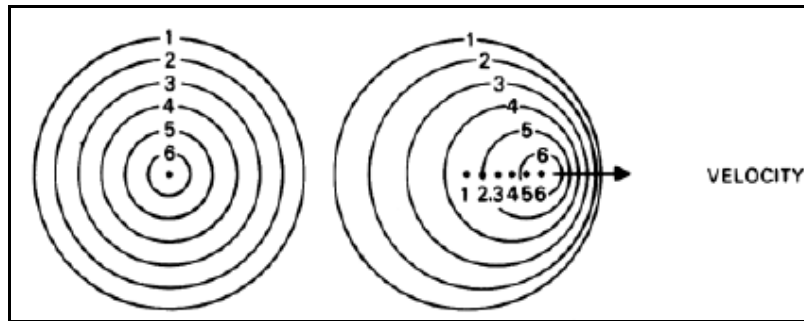


Figure 11. Compression of Wave (From [3])

The frequency of the wave increases as the wave becomes more compressed due to the inverse relationship between wavelength and frequency. This causes a carrier frequency shift (increase) that is directly proportional to the target velocity in the direction shown in Figure 11.

Considering radars that are stationary on the ground, the only possible relative motion occurs as the target moves. Since fixed-site ground-based radars are unable to move, they have an advantage with respect to ground clutter. In other words, the waves that are reflected from the ground do not create Doppler shift, so the discrimination between the target echoes and ground clutter is relatively easy as it needs only to

differentiate between the frequency content of fixed and moving targets. On the other hand, the circumstances are very different for airborne radars as both the target and the airborne radar itself are moving. This causes a relative motion that relates to both (Figure 12) [3]. It is also harder for airborne radars to discriminate between ground clutter and moving target echoes as both have a Doppler shift associated with their motion. The solution to this problem is to compare the relative magnitudes of Doppler shifts and interpret the result in terms of their relative changes in motion.

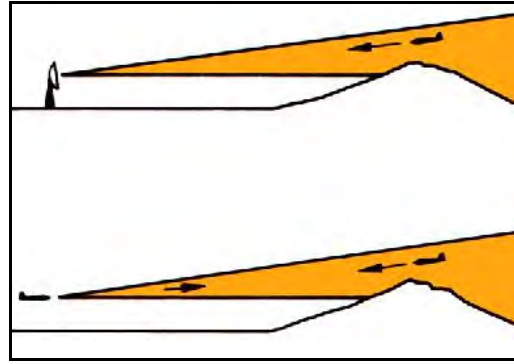


Figure 12. Relative Motion in Ground and Airborne Platforms (From [3])

Doppler shift in a radar receiver can be interpreted as the difference between the frequencies of transmitted and received pulse waveforms. Therefore, we can formulate a measure of Doppler frequency as shown in Eq. (2.12) where f_d is Doppler shift, f_t is the transmitted frequency and f_R is the frequency received by the radar on the ground.

$$f_d = f_R - f_t \quad (2.12)$$

Using the relativity theory, we can write the equation for the received frequency as in Eq. (2.13) where f_t is the transmitted frequency, v_R is the radial velocity of the airborne platform in the direction of radar and c is the speed of light.

$$f_R = f_t \frac{c + v_R}{\sqrt{c^2 - v_R^2}} \quad (2.13)$$

Assuming that the radial velocity is much less than the speed of light and the total Doppler shift is twice the one-way shift, we can rearrange the equation as in Eq. (2.14) [4], [6]. Eq. (2.14) is a commonly used representation for the relationship between radial velocity motion and the measurable Doppler frequency that motion creates.

$$f_d = \frac{2f_t v_R}{c} = \frac{2v_R}{\lambda} \quad (2.14)$$

2. Types of Doppler Radar

The radar types within the Doppler radar class can be summarized as in Figure 13.

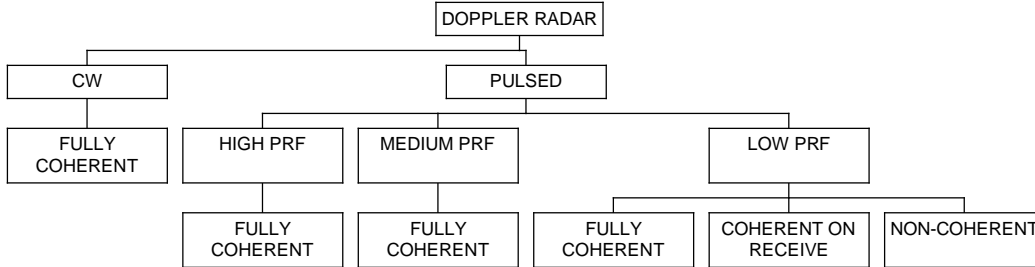


Figure 13. Types of Doppler Radar (From [4])

a. CW Radars

As shown in Figure 13, radars that measure Doppler are not limited to pulse radars. Continuous Wave (CW) radars radiate their waves continuously, as their name implies. CW radars have the ability to measure the instantaneous rate of change in the target velocity by measuring the Doppler shift of the received signal. One of the most commonly used applications of CW radars is the speed gun as used by law enforcement and in other civilian applications. By using the speed gun and frequency changes between the transmit and receive waves, the portion of the speed that is in the direction of the radar can be determined [12].

One of the advantages of CW radars is that they are much simpler in design than pulse radars. On the other hand, CW radars are limited in range due to interference between the signal at the transmitter and the receiver. Isolation between the transmitter and the receiver is necessary for a CW radar to use higher amounts of power. In contrast, pulse radar has no such limitation since the transmitter remains in a stand-by mode when the receiver is on and no interference occurs.

The major disadvantage of CW radar is the cost of two antennas. In addition, another disadvantage is the inability to measure range due to its narrow spectrum. In order to measure range, timing marks should be used so that the time of

transmission and return can be identified. The sharpness or the distinctness of the marks defines the accuracy of the measurement. However, the transmitted spectrum gets wider as the marks get more distinct. Thus, a finite spectrum has to be transmitted in order to measure range or transit time. The ideal method for widening the CW spectrum is modulating either its amplitude, phase, or frequency. Pulse radar is the common application of amplitude modulation. Accuracy of the range measurement depends on the narrowness of the pulse as it broadens the transmitted spectrum. Another technique is to use frequency modulation. In this technique, frequency changes stand for the timing marks and frequency difference of the transmitted and the received signal is proportional to the transit time. The accuracy of the transit time measurement and amount of spectrum that is transmitted increase as the deviation of transmitter frequency increases.

One of the most common applications of FM-CW is the aircraft radio altimeter that is used to measure the vertical height of the aircraft above ground. The frequencies that are reserved for radio altimeters are between 4.2 and 4.4 GHz [13].

b. Pulse Doppler Radars

Pulse Doppler radars have gained in significance due to technological developments in digital signal processing and the maturation of reliable high-power microwave power sources. The basic principle involved in pulse Doppler radars is utilizing the Doppler effect to differentiate targets from clutter by using their inherently different velocity signatures. In airborne applications, the ability to discriminate between velocities through Doppler provides a better “look-down-shoot-down” capability [2].

Pulse Doppler radar design is more complex than CW radar, but it also provides several clear advantages. Time gating of the receiver, which is the most important advantage, prevents transmitter leakage into the receiver by turning off the transmitter while listening for echoes. Time gating also enables the radar to use a single antenna both for transmitting and receiving. Another form of time gating, called “range gating” is also used in pulse Doppler radars. Range gating separates the interpulse period (listening period) into many individual range gates. Range gating between transmit pulses is useful in elimination of excessive receiver noise from the many returns coming back

from unwanted targets (or from clutter). Range gating is also used in measuring range by characterizing the time elapsed from pulse release to the arrival within a specific range bin. Basic characteristics of pulse Doppler radars rely upon coherent transmission and reception of pulses [1].

Pulse Doppler radars, equipped with array antennas and modern processors, are able to track multiple targets at the same time while searching for additional targets. In addition, moving ground targets can be detected and tracked. Synthetic Aperture Radar (SAR) and Inverse Synthetic Aperture Radar (ISAR) pulse Doppler designs are capable of producing high-resolution target images. A general description of pulse Doppler applications and their requirements are shown in Table 3 [1], [3], [8].

Radar Application	Requirements
Airborne or spaceborne surveillance	Long detection range; accurate data range
Airborne interceptor or fire control	Medium detection range; accurate range, velocity, and angle data
Ground-based surveillance	Medium detection range; accurate range data
Battlefield surveillance (Slow moving target detection)	Medium detection range; accurate range, velocity data
Missile seeker	Short detection range; accurate velocity and angle rate data; may not need true range information
Surface-based weapon control	Short range; accurate range, velocity data
Meteorological	Good velocity resolution
Missile warning	Short detection range; very low false alarm rate

Table 3. Pulse Doppler Applications and Requirements (From [1])

Pulse Doppler radars can be categorized according to the applications as shown in Table 3 or based on the waveforms they use, for example using PRF categories such as low, medium and high. PRF flexibility allows selection of the unambiguous performance range. Low PRF radars provide accurate, unambiguous range measurements over very long ranges whereas they have highly ambiguous velocities. Low PRF radars are also called “Moving Target Indication (MTI).” Despite the similar operation principles, MTI radars are not considered to be pulse Doppler radar. Medium PRF radars are ambiguous both in range and velocity, but when compared to low PRF radars they provide higher average transmitted power and better velocity discrimination. High PRF radars are better in average transmitted power and velocity, but they are highly ambiguous in range [1], [8], [14], [15]. A detailed examination of pulse Doppler radars in airborne applications is explained in the following section.

C. AIRBORNE PULSE DOPPLER RADAR

1. PRF Selection

PRF is one of the most important parameters of pulse Doppler radars. The selection of PRF according to the radar objectives determines the extent of ambiguities in range and Doppler frequency.

a. Range Ambiguities

Range ambiguities occur if the interpulse period, T_p , which is inversely proportional to the pulse repetition frequency [Eq. (1.2)], is shorter than the return time of the echoes of any preceding pulse. In other words, radar is unable to determine which echo belongs to which pulse, and therefore unable to resolve range without ambiguity. If the second pulse is transmitted before the echo of the first returns to radar, then the target will show up at a shorter distance than it really is, leading to an apparent range. Therefore, there are more range ambiguities for high PRF radars since the interpulse periods (T_p) are shorter than either low or medium PRF radar. If an echo is received during the first interpulse period, it is called “single time-around echo.” Any echo received that is not due to the most recent pulse is called “multiple time-around echo” [3].

Maximum unambiguous range, R_u , is the longest range for a chosen PRF from which only single time-around echoes can be received. In order not to have range ambiguities, either low PRFs can be chosen or other methods of pulse elimination can be applied (with a corresponding increase in radar complexity). For the condition where targets beyond the maximum unambiguous range are not of concern, all returns beyond this range can be eliminated (Figure 14) [3].

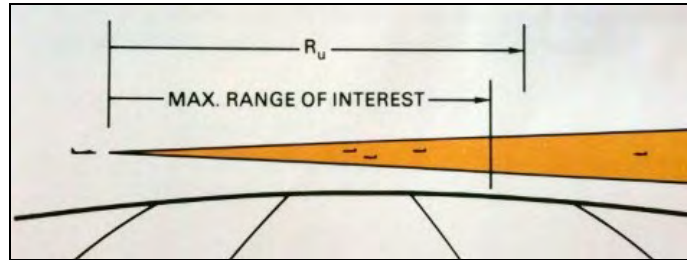


Figure 14. Eliminating Ambiguous Return (From [3])

PRF adjustment can be used to identify and reject the targets beyond R_u by means of using two or more different PRFs at different time intervals. This works because the apparent ranges of the targets beyond R_u are dependent on PRF, but the true target ranges are not. If the target is beyond R_u , the received echoes from the true target are not due to any preceding transmission pulse. Thus, it is the apparent range of the target, not the true range, which is affected by the change in PRF. On the other hand, the opposite condition holds for the targets within R_u . Since the targets beyond R_u are rejected, the ranges of the remaining targets are unambiguous (Figure 15). As shown in the provided figure, apparent range varies each time the PRF is adjusted while the true range from release at A1 (shown in the middle of the diagram) is constant for both PRFs. The trade-off for PRF adjustment is that time on target must be divided between the multiple PRFs, which inevitably reduces maximum detection range and sensitivity [3].

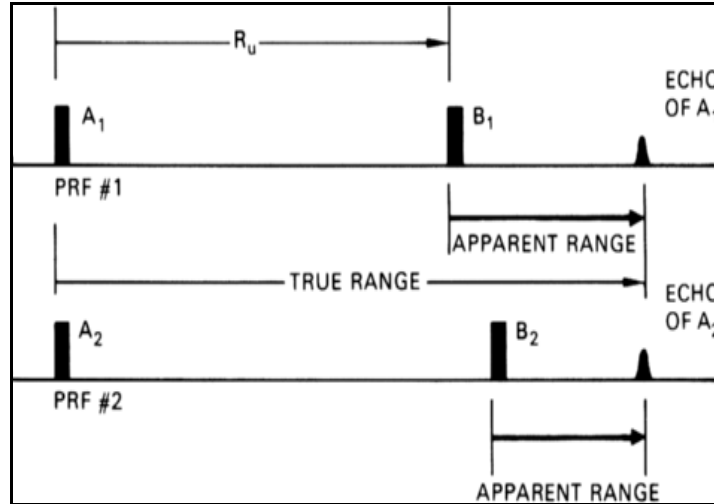


Figure 15. Apparent Ranges (From [3])

For pulse repetition frequencies f_1 and f_2 , if assumed that unambiguous ranges are R_{un1} and R_{un2} and apparent ranges are R_1 and R_2 , respectively, then the true range of the target is the value that is consistent in both Eq. (2.15) and Eq. (2.16). Although two PRFs are sufficient to resolve range ambiguity, three or more PRFs are preferred for better accuracy [8].

$$R_{true} = R_1, \text{ or } (R_1 + R_{un1}), \text{ or } (R_1 + 2R_{un1}), \text{ or } \dots \quad (2.15)$$

$$R_{true} = R_2, \text{ or } (R_2 + R_{un2}), \text{ or } (R_2 + 2R_{un2}), \text{ or } \dots \quad (2.16)$$

A simple diagram of range versus PRF is depicted in Figure 16, assuming a single PRF is used rather than multiple PRFs. The green area under the unambiguous range curve includes all possible PRFs corresponding to true range where range is unambiguous. Range is ambiguous for any areas above the curve that bounds the green area [3].

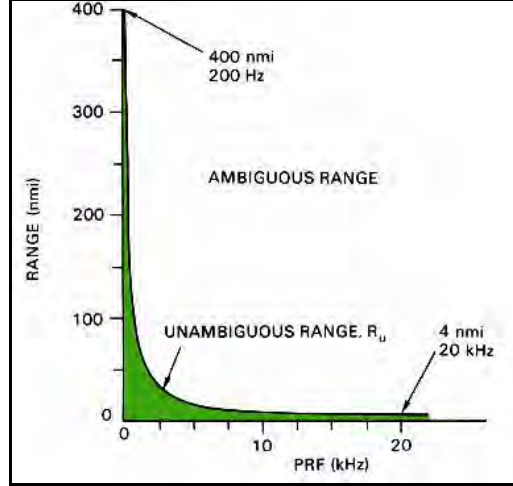


Figure 16. PRF Vs. Range (From [3])

b. Doppler Ambiguities

Pulse systems have transmit spectrums consisting of spectral lines, which are separated by the PRF. These spectrums will also shift in content based on Doppler frequency, which changes as a function of target radial velocity. If the PRF is higher than the highest Doppler frequency, it is assumed that any spectral line to which a radar's Doppler filter is tuned may be the next lower line of the transmitted signal shifted by the target's Doppler frequency. Otherwise, there will be Doppler ambiguities in the receive spectrum. In this undesired case, lower PRFs have more Doppler ambiguity due to their narrow spaced spectral lines. The extent of Doppler ambiguity is related not only with PRF but also with the wavelength and target opening-closing velocity rates. Range rate of a target, \dot{R} , for a head-on approaching (closing) target is shown in Eq. (2.17), where V_R is the velocity of radar and V_T is the velocity of target [3], [6].

$$\dot{R} = -(V_R + V_T) \tag{2.17}$$

For tail-on situation, the difference of the velocities is used. Consequently, the Doppler frequency is shown in Eq. (2.18).

$$f_d = -2 \frac{\dot{R}}{\lambda} = 2 \frac{V_R + V_T}{\lambda} \tag{2.18}$$

Considering a $\sin(x)/x$ envelope, the Doppler measurement will be ambiguous if the Doppler frequency of the target is high enough that the adjacent spectral

line moves inside the Doppler band of interest. With an increase in Doppler frequency, a Doppler shifted return of the true target moves out of the passband (Figure 17) and a lower sideband lobe enters [15], [16]. The maximum unambiguous velocity is shown in Eq. (2.19). Maximum closing rates versus PRF with an assumed radar velocity of 1,000 knots (514.44 m/s) and three different types of radars that have different wavelengths are shown in Figures 18, 19 and 20 [3].

$$v_u = \pm \frac{\lambda f_{d_{\max}}}{2} = \pm \frac{\lambda f_p}{4} \quad (2.19)$$

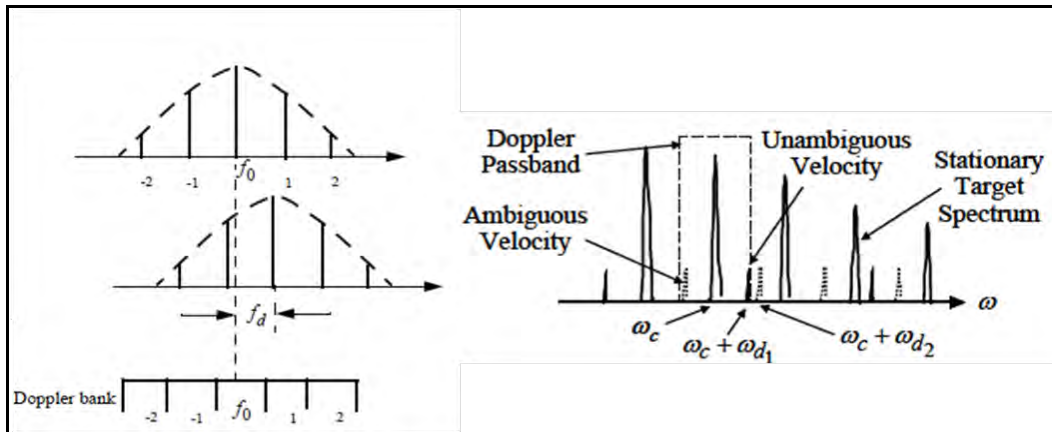


Figure 17. Velocity Ambiguities (After [16])

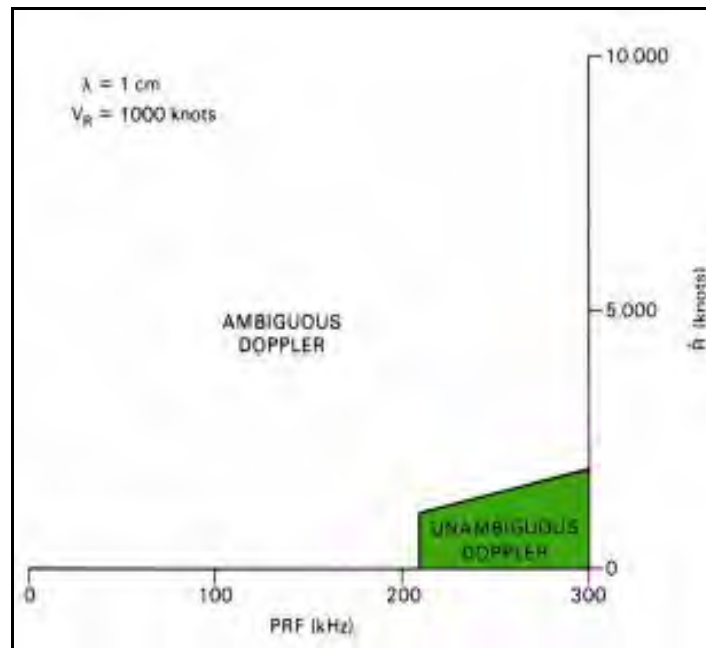


Figure 18. Max. Unambiguous Doppler, $\lambda=1$ cm (From [3])

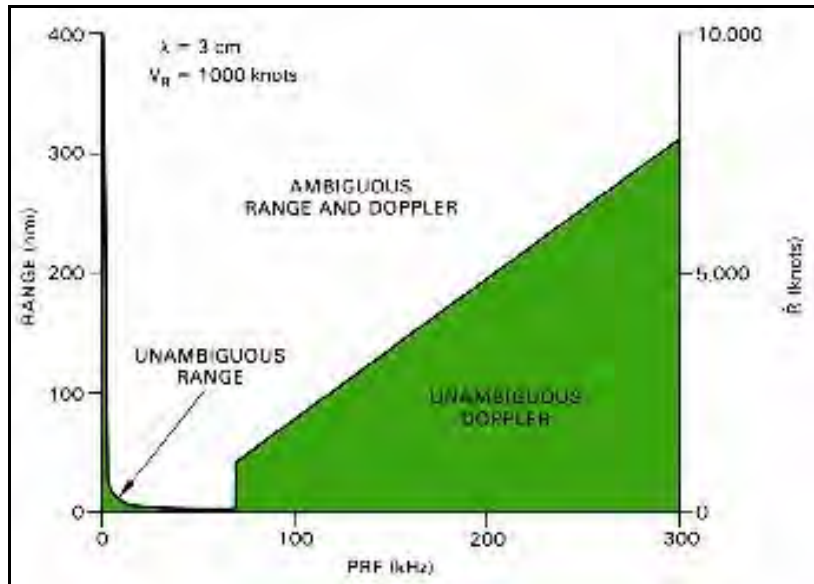


Figure 19. Max. Unambiguous Doppler, $\lambda=3$ cm (From [3])

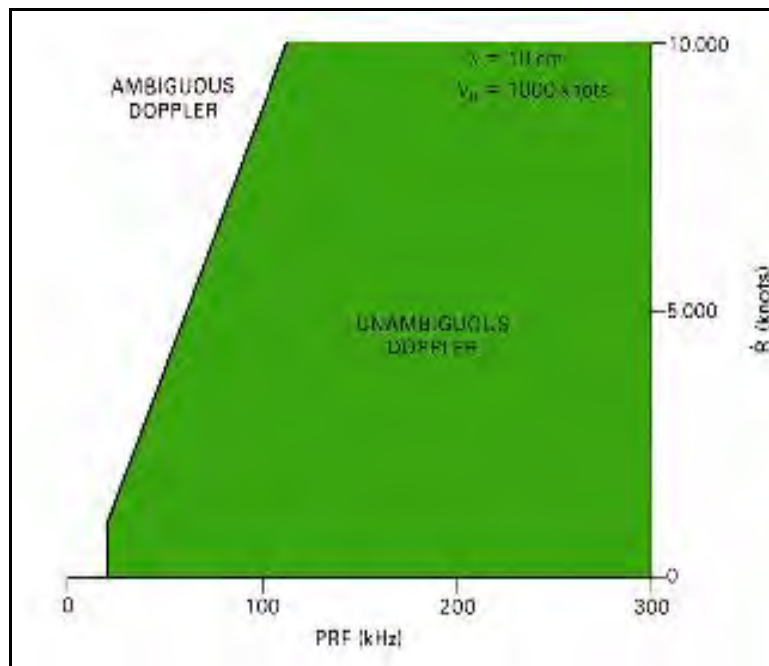


Figure 20. Max. Unambiguous Doppler, $\lambda=10$ cm (From [3])

The green zones under the provided curves involve unambiguous Doppler frequencies for corresponding closing rates and PRFs at a specific target velocity and radar wavelength. If an assumed radar velocity of lower magnitude is used, the

unambiguous Doppler areas will be smaller (see Eq. (2.18)). From the provided curves at 1,000 knots, as the Doppler frequency is inversely proportional to wavelength, the higher the wavelength is used, the bigger the area of unambiguous Doppler grows (see Figures 19 and 20) [3]. Although clutter rejection is difficult with both range and Doppler ambiguities, use of a wide range of PRFs and choosing them carefully can help to overcome velocity and range ambiguity problems.

c. PRF Categories

Since the choice of PRF is highly important for radar performance, airborne radars are categorized into three groups: Low, medium and high. These categories do not necessarily stand for any specific numerical limits but are used instead to identify the extent of ambiguities both in range and Doppler. The maximum range that low PRF radars can handle is inside the first part of the range zones. The performance range of the low PRF radar is ambiguous for range returns beyond this point. The opposite condition holds for high PRF Doppler radars as this range limit moves closer to the radar and targets are now generally ambiguous. The Doppler frequency resolution of these two radar schemes (low and high PRF) is just the opposite of the described range ambiguity [3]. Medium PRF Doppler radar involves a compromise design that is recognized as ambiguous both in the range and Doppler domains. The main advantage of medium PRF radar is that it has better performance than low PRF radars against closing targets and better performance than high PRF radars against tail-aspect targets [5]. This feature makes medium PRF radars uniquely suitable where all aspect coverage is needed.

Radar category classification for a given PRF is different for various operating conditions. For the condition that the maximum target range extends to a 20 nmi limit, a PRF of 4 kHz is considered “low,” whereas it is medium for a range greater than 20 nmi (Figure 21) [3].

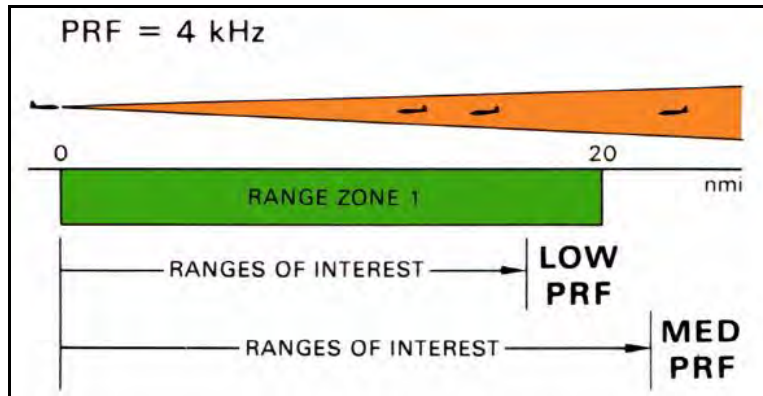


Figure 21. Different PRF Categories With Max. Target Range (From [3])

2. Low PRF Mode

The range of low PRF for typical X-band radars is from 1 to 3 kHz [8]. Low PRF is mostly used for air-to-ground applications. Although they are not preferred for all air-to-air operations, there are a few areas in which low PRF radars have significant advantages against medium and high PRFs, such as early warning. It is possible for an airborne multimode radar to have numerous low PRF modes as listed in Table 4 [3], [4].

Radar Mode	Typical System Function
Coherent Modes	
Doppler	Airborne Moving-Target Detection Ground Moving-Target Detection
Doppler Beam Sharpening	Improved Resolution ground map for navigation
Synthetic Aperture	Stationary Target Detection
Non-Coherent Modes	
Ground Map	Navigation
Terrain Avoidance	Covert Navigation
Air-to-Air Ranging	Short-Range Gun and Missile Attack
Air-to-Ground Ranging	Bomb Delivery
Terrain Following	Covert Navigation

Table 4. Low PRF Modes (From [4])

One of the most important advantages of low PRF is precise range measurement by pulse delay ranging due to the unambiguous range that is available by radars that use low PRFs. The other advantage is rejection of sidelobe returns through range resolution. However, most aircraft radars use small antennas with short wavelengths and they operate on platforms with a high ground speed. Thus, with the use of low PRFs, rejection of clutter also rejects target returns, which the radar must capture. It is also impossible to fully resolve ambiguities in Doppler with low PRF radar. Moreover, ground moving targets also interfere with the radar when low PRF is used. Low PRF is ideal to use in ground mapping since the mainlobe ground return is the primary concern. The advantages and limitations of low PRF are briefly stated in Table 5 [3], [4].

Advantages	Limitations
Precise range measurement	Highly ambiguous Doppler
Fine range resolution	Poor air-to-air look down capability
Good for air-to-air look up	Low probability of detection and high false alarm rate in look down missions
Simple data processing	
Good for ground mapping	High peak power or pulse compression ratio
Range gating rejects sidelobe clutter	Ground moving targets can be a problem
Unambiguous range	

Table 5. Low PRF Mode Characteristics (After [3], [4])

3. High PRF Mode

The main characteristic of high PRF is that there are no ambiguities in Doppler; however, this characteristic results in a range that is highly ambiguous. Typical X-band high PRF radar ranges from 100 kHz to 300 kHz, having the widest range among other categories [8]. With the use of high PRF, mainlobe clutter (MLC) can be rejected and target echoes with different Doppler frequencies than the clutter can also be acquired. Another significant advantage of high PRF is the clutter free region that can emerge when

the bands of the clutter spectrum are adequately separated (Figure 22). This lets high aspect targets show up in the clutter-free region [3], [6].

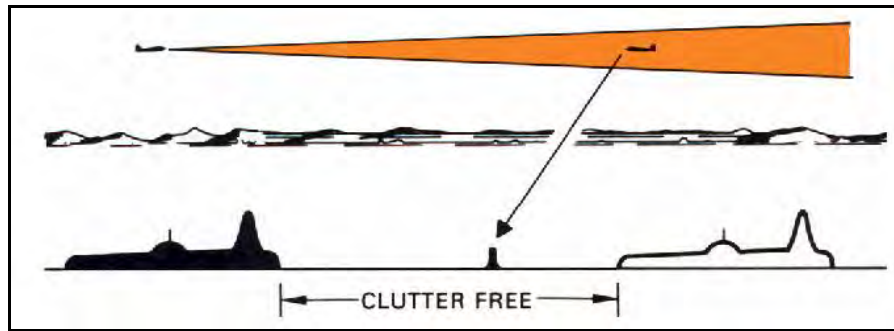


Figure 22. Clutter-Free Region Due to High PRF (From [3])

High average power is also available by employing high PRF. Higher average power, without using high peak power and a high pulse compression rate, is due to the use of increased duty factor by using higher PRFs, rather than longer pulsewidths. Although high PRF provides long detection range for closing targets even in the presence of clutter, it is generally poor against tail-aspect targets when sidelobe clutter (SLC) is strong (Figure 23) [3].

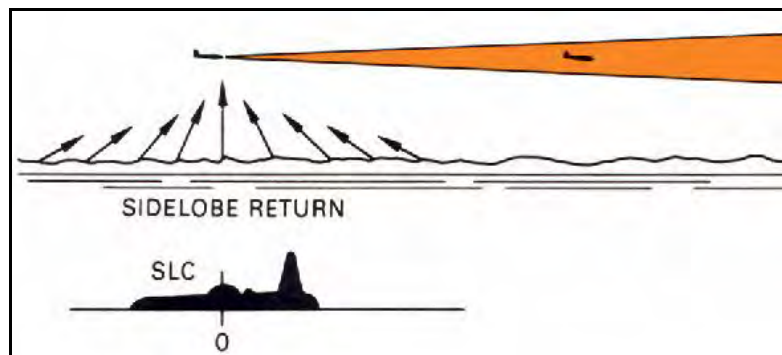


Figure 23. Sidelobe Return in High PRF Mode (From [3])

In situations where an aircraft is flying at low altitude over an area with a backscatter coefficient that is relatively high, and the cross section of the target is small, the echoes of the target may be lost in clutter (as shown in Figure 23). Since high PRF is highly ambiguous in range, it is hard to perform pulse delay ranging [3]. The advantages and limitations of high PRF mode are briefly described in Table 6.

Advantages	Limitations
Good nose aspect capability	Highly ambiguous range
Unambiguous Doppler	Complicated and less accurate ranging
Mainlobe clutter rejection without rejecting target echo	Sidelobe clutter reduces tail aspect detection sensitivity
Higher average power and longer detection range as a result of high duty factor	Zero closing rate targets may be rejected with altitude return
Illumination for semi-active missiles	

Table 6. High PRF Mode Characteristics (After [3], [4])

4. Medium PRF Mode

Medium PRF, which ranges from 10 to 30 kHz for typical X-Band radars [8], is used as a compromise for overcoming some of the previously mentioned performance limitations of both low and high PRFs. The characteristics of medium PRF are examined in detail in Chapter III.

D. AIRBORNE PULSE DOPPLER RADARS EMPLOYING MEDIUM PRF

A few examples of medium PRF airborne radars are briefly described below in order to represent available medium PRF systems that have been produced and used so far. These multimode radars, having various operating modes with respect to the objectives of the multiple missions they must perform, utilize a wide range of PRFs, specifically low, medium and high PRFs. Low PRF mode is commonly used for air-to-surface missions and medium/high PRF modes are used for air-to-air engagements. When high PRF mode is used, detection range increases against high aspect targets and the radars, using the velocity search mode, detect targets at longer distances compared to other PRF modes. Once the target detection is complete, radars start to use medium PRF in range-while-search mode so that they acquire additional information about range and angle of targets with any aspect [17]. Various modes, some of which are mentioned above, are available in these radars with different choice of PRFs.

1. AN/APG-63/70

The AN/APG-63 and AN/APG-70 are airborne pulse Doppler radars that operate at X-band. Both of these multimode radars have an all-weather operational capability. They are produced by Raytheon, and are currently being used in the F-15 fighter aircraft. All of the F-15A/Bs and early versions of F-15C/Ds employ the AN/APG-63. The AN/APG-70, which is a redesign of the AN/APG-63, is currently being used in the later models of F-15C/Ds and all of the F-15E/I/S models [18], [19].



Figure 24. AN/APG-70 (From [20])

2. AN/APG-66/68

The AN/APG-66 is the early version of the AN/APG-68 that is used in F-16A/Bs. It was redesigned as the AN/APG-68 with major upgrades and employed in F-16C/Ds. Both of the radars are X-band airborne pulse Doppler radars. They are designed by Northrop Grumman. The AN/APG-68 has had several upgrades to the present configuration and has been produced in several versions, which are used in various blocks of F-16s. The United States, Israel, Turkey, Greece, and Pakistan are just some of the many countries that have F-16s in their inventories [21].



Figure 25. AN/APG-68 (From [22])

3. AN/APG-65/73

The AN/APG-65 and 73 are X-band airborne pulse Doppler radars with all-weather capability. They are both produced by Raytheon, with the AN/APG-73 being an upgraded version of the AN/APG-65. The AN/APG-65 is used in F/A-18A/Bs, upgraded F-4s, and AV-8Bs. The AN/APG-73 is used in F/A-18C/Ds and early versions of F/A-18E/Fs [23].



Figure 26. AN/APG-73 (From [24])

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III. MEDIUM PRF CHARACTERISTICS

As described previously, medium PRF radar is used as a compromise between low and high PRF in order to overcome some inherent deficiencies common to either low or high PRF systems. Medium PRF ranges from 10 to 30 kHz for a typical X-band radar [8]. Medium PRF modes are significant since they are capable of detecting targets with slow closing rate from a high speed platform [4]. The main performance feature of medium PRF is that it is ambiguous both in range and Doppler. A graph of unambiguous range versus unambiguous velocity is shown in Figure 27. The reason why medium PRF is chosen is that medium PRF improves the capability of radar in dealing with mainlobe clutter and ground moving targets compared to low PRF, and medium PRF also improves the capability in dealing with sidelobe clutter in low closing rates compared to high PRF [3].

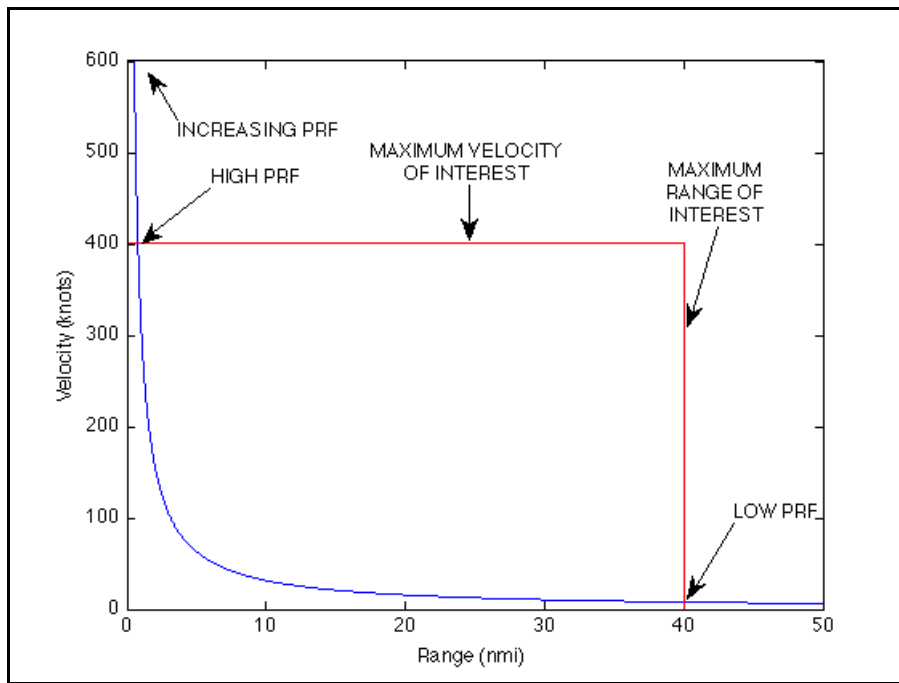


Figure 27. Unambiguous Range Vs. Unambiguous Velocity (From [4])

A. WAVEFORM CHARACTERISTICS

1. Range Profile

Using an X-band airborne radar, with an assumed PRF of 10 kHz and range of 24 nmi, a range profile is shown in Figure 28. Depending on the PRF used, range is divided into three zones.

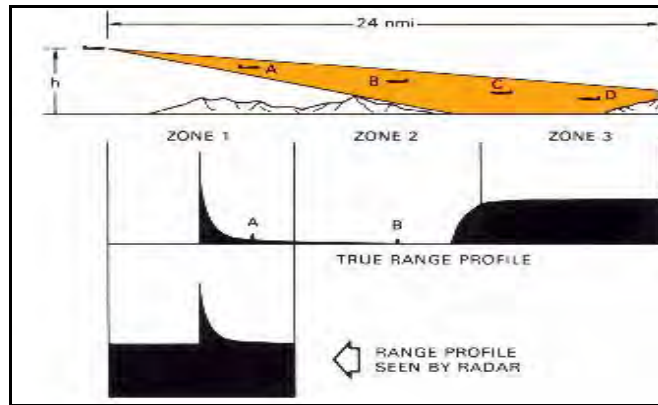


Figure 28. Range Profile (From [3])

As seen in the figure, none of the targets can be detected since they are covered with clutter. In this case, ground clutter covers the entire interval. The only solution for clutter rejection lies in the ability of the radar to use Doppler frequency discrimination [3].

2. Doppler Profile

Doppler profile of a medium PRF radar includes lines of mainlobe clutter that are separated by the PRF. The difference between low and medium PRF Doppler profiles is mainlobe clutter lines are spaced farther apart in medium PRF (Figure 29). Some of the target returns and sidelobe clutter can be seen between two lines, but the remaining ones are masked with mainlobe clutter that is periodic in frequency, with separation of the PRF [3].

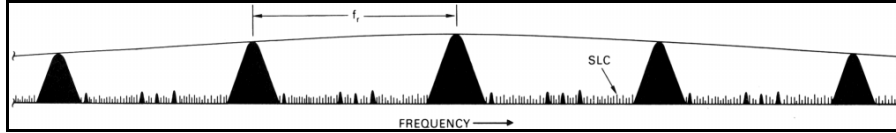


Figure 29. Doppler Profile (From [3])

B. CLUTTER REJECTION

1. Mainlobe Clutter Rejection

The spectral lines of mainlobe clutter are more widely separated in medium PRF than in low PRF radar, and there are more clear target detection regions between those lines in medium PRF. In cases where the mainlobe clutter is wide, it can be rejected depending on Doppler frequency. Range profile with a removed mainlobe clutter is shown in Figure 30 (Target A) where only the target at short range can be detected [3].

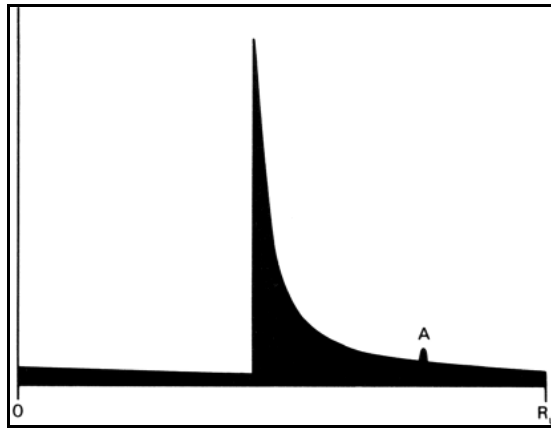


Figure 30. Range Profile With Removed MLC (From [3])

2. Sidelobe Clutter Rejection

The sidelobe clutter in the provided scenario consists of parts with different ranges and angles. Thus, a differentiation between the sidelobe clutter and target echoes can be made if the return is sorted by both Doppler frequency and range. Sampling is the method for sorting by range. Returns coming from narrow strips of ground at a fixed range are separated by range gates. In order to sort by Doppler frequency, a bank of Doppler filters must be applied to the output of every range gate. The filters are used for

separating the returns coming from strips of ground among lines with relatively fixed angles according to the velocity of the radar [3].

C. RANGE AND DOPPLER BLIND ZONES

1. Doppler Blind Zones

Unlike low PRF, Doppler blind zones are less important for medium PRF as only a small part of the Doppler frequency spectrum is covered by mainlobe clutter. If necessary, the number of Doppler blind zones can be reduced by switching between PRFs. On the other hand, each PRF that is used helps to resolve the ambiguities in range and eliminate ghosts. Radars use different waveforms that they cycle through a certain number of PRFs, using some predefined number that has to be clearly known. The most common formula for ambiguity resolution is known as the “3 out of 8.” As long as the target is clear on three of eight PRF cycles and the detection threshold is exceeded by those, then the target is considered as detected [3], [4]. The right side of Figure 31 shows the eight PRFs that cycle and the blind zones with regard to each PRF. A target must be in the clear parts between these blind zones for at least three PRFs in order to be detected.

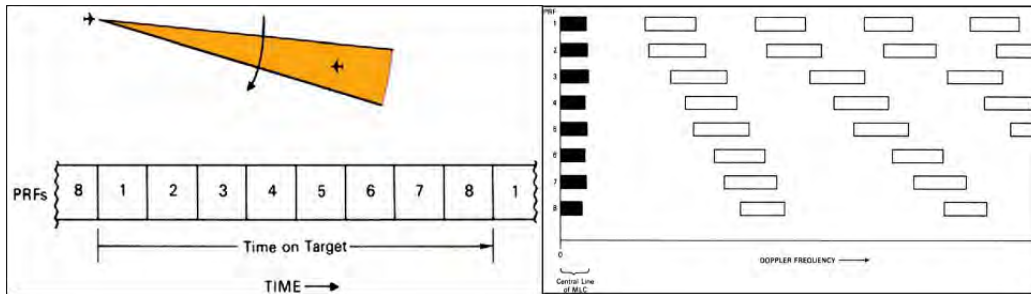


Figure 31. Three Out of Eight Waveform (After [3])

2. Range Blind Zones

The strength of clutter, which depends on the gain of the radar antenna sidelobes, the natural environment and the radar altitude as well, determines the extent of range blind zones. Range blind zones increase as the clutter strength gets higher. Targets will remain undetected where clutter is stronger than the target echo. There are other range blind zones that occur due to eclipsing by transmitted pulses. The radar receiver remains

in stand-by mode as the radar is transmitting. Targets may not be detected if the returns arrive at the blanked time of the receiver. Although the blind zones are not wide, they become significant as the pulsewidth of the transmitted pulse increases, as is possible in some medium PRFs.

When the PRF is changed, the positions of range blind zones change as well. In order for a target to be detected, it must be in both of the clear regions of range and Doppler for the same PRF sets [3]. The black regions in Figure 32 represent the blind zones, whereas the remaining white part is the range and Doppler clear area.

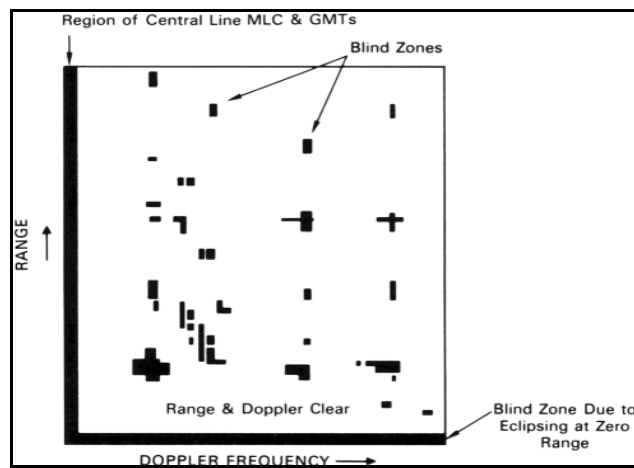


Figure 32. Target Detection With 3:8 (From [3])

D. ADVANTAGES AND LIMITATIONS

Medium PRF has ambiguities both in range and Doppler. However, the number of zones with possible targets is limited, which also means that both range and Doppler ambiguities can be resolved. Medium PRF transmission modes are considered to produce a medium level of energy (relative to high PRF and CW modes). The modes that employ medium PRF usually operate at medium/short ranges [6]. Medium PRF is especially useful for detection of targets with a tail-aspect in the presence of mainlobe and sidelobe clutter. Therefore, medium PRF radars provide good all aspect coverage [3].

Pulse delay ranging with resolution of range ambiguities is possible in medium PRF radar. Since the mainlobe clutter (MLC) spectral peaks are separated widely, ground moving targets can be rejected.

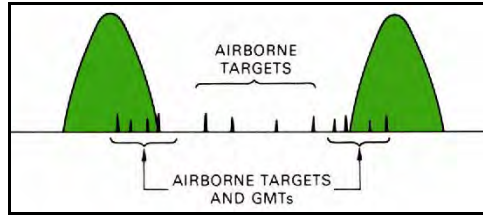


Figure 33. GMT Rejection (From [3])

On the other hand, targets of both aspects may present problems with close-in sidelobe clutter due to range and Doppler ambiguities (Figure 34). However, using several PRFs can overcome this problem whereas the integration time for each of the PRFs is reduced and causes the maximum detection range to be limited. Since medium PRF is commonly used at “moderate to low altitudes, in lookdown situations, or in tail chases” [3], this will not be a serious problem.

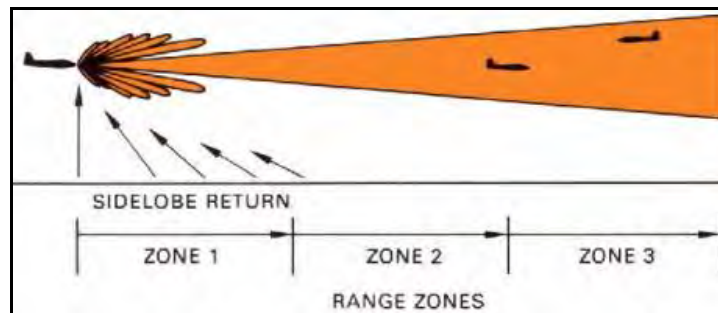


Figure 34. Close-In Sidelobe Clutter (From [3])

IV. SIMULATION

The simulation described in this chapter focuses on the use of medium pulse repetition frequencies (PRF) as a compromise between low and high PRFs in a radar design with regard to the range and velocity ambiguities involved.

A. DESCRIPTION

MATLAB codes are written in order to display how the ambiguities in both domains (range and velocity) vary by switching between eight medium PRFs for a typical X-band airborne radar with an operating frequency of 10 GHz. Results will be based on evaluation of the ambiguity function [25].

The simulation consists of three parts. In the first part, it is assumed that no clutter is present. Ambiguity diagrams and contours of the selected eight medium PRFs will be plotted separately within given parameters. After that, obtained contours from the medium PRF simulation will be compared. In the end, a model using multiple medium frequencies with pulse-to-pulse switching method will be created and its effect with regard to the ambiguities will be examined.

In the second part of the simulation, the effect of clutter is added to the first part of the simulation described in the preceding paragraph, which was clutter-free. The objective of the second part is to show the effect of clutter with regard to decreasing the detection performance of the radar. These results will be compared with the results from the first part of the simulation.

In the final part of the simulation, the objective is to acquire the optimum results with regard to detection performance under a specified set of circumstances. An optimization process will be conducted and the best eight of all X-band medium pulse repetition frequencies will be selected within the specified conditions.

After a brief discussion about the ambiguity function, each part of the simulation will be explained. Simulation parameters and the assumptions are presented separately

for each part. Several conclusions are made depending on the obtained results, which are also consistent with the prior assumptions made in establishing the medium PRF radar simulation.

B. AMBIGUITY FUNCTION

The radar ambiguity function shows the output of the radar receiver's matched filter and presents a description of the interference that is caused by the range delay and Doppler shifts. The evaluation of the ambiguity diagram at the origin, where the time delay and the Doppler shift are equal to zero, produces a matched filter output that is identical to the reflected signal from the target. This means that nominal target returns are at the origin of the ambiguity diagram. The values of the ambiguity function at nonzero time delays and Doppler shifts represent the returns of the target with a different range and velocity when compared to the nominal target [15]. The modulus square of the matched filter output is called the ambiguity function where $x(t)$ is the signal, τ is the time delay and f_d is the Doppler frequency [25].

$$|\chi(\tau, f_d)|^2 = \left| \int_{-\infty}^{\infty} x(t)x^*(t-\tau)e^{j2\pi f_d t} dt \right|^2 \quad (4.1)$$

The ambiguity function is usually used for studying the impact of waveform changes in both range and Doppler. The range and Doppler resolutions of radar waveforms can also be determined by using the ambiguity function [25]. The properties of the radar ambiguity function are listed where E_x is the energy of the signal [Eq. (4.2)].

$$E_x = \int_{-\infty}^{\infty} |x(t)|^2 dt \quad (4.2)$$

- The ambiguity function has a maximum value at the origin $(\tau, f_d) = (0, 0)$ and is equal to $(2 E_x)^2$ [25].

$$\max \left\{ |\chi(\tau, f_d)|^2 \right\} = |\chi(0, 0)|^2 = (2E_x)^2 \quad (4.3)$$

$$|\chi(\tau, f_d)|^2 \leq |\chi(0, 0)|^2 \quad (4.4)$$

- The ambiguity function is symmetric about the origin in both time delay and Doppler domains [25].

$$|\chi(\tau, f_d)|^2 = |\chi(-\tau, -f_d)|^2 \quad (4.5)$$

- The overall volume under the ambiguity function is constant [25].

$$\iint |\chi(\tau, f_d)|^2 d\tau df_d = (2E_x)^2 \quad (4.6)$$

- Considering $X(f)$ is the Fourier transform of the signal $x(t)$, then we can obtain [25],

$$|\chi(\tau, f_d)|^2 = \left| \int X(f) * X(f - f_d) e^{-j2\pi f \tau} df \right|^2 \quad (4.7)$$

The ideal radar ambiguity function consists of a single spike, which has infinitely small width and has a peak only at the origin ($\tau = f_d = 0$), which is where the true target is located. The function is zero elsewhere. However, an ideal ambiguity function cannot exist in practice since the function must have a finite peak value of $(2E_x)^2$ [15].

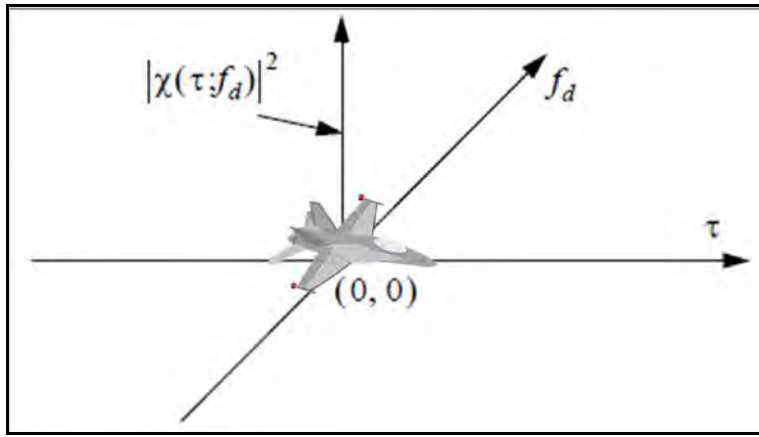


Figure 35. Ideal Ambiguity Function (After [15])

The complex envelope of a single pulse radar waveshape, $x(t)$, and the normalized ambiguity function of a single pulse waveform are shown in Eq. (4.8) and Eq. (4.9), respectively, where τ is the time delay and τ_0 is the pulsewidth [25].

$$x(t) = \frac{1}{\sqrt{\tau_0}} \text{Rect}\left(\frac{t}{\tau_0}\right) \quad (4.8)$$

$$|\chi(\tau, f_d)|^2 = \left| \left(1 - \frac{|\tau|}{\tau_0}\right) \frac{\sin(\pi f_d (\tau_0 - |\tau|))}{\pi f_d (\tau_0 - |\tau|)} \right|^2 \quad |\tau| \leq \tau_0 \quad (4.9)$$

The ambiguity function for a coherent pulse train consisting of N pulses, where $x(t)$ is the normalized individual pulse and is identical to the single pulse radar waveshape

form shown in Eq. (4.8), τ_0 is the pulsewidth and T is the pulse repetition interval, is shown in Eq. (4.10) for $\tau_0 < T/2$. The length of the pulse train for N pulses is $(N-1)T$ seconds [25].

$$|\chi(\tau, f_d)| = \frac{1}{N} \sum_{q=-(N-1)}^{N-1} |\chi_1(\tau - qT, f_d)| \left| \frac{\sin[\pi f_d (N - |q|T)]}{\sin(\pi f_d T)} \right| \quad |\tau| \leq NT \quad (4.10)$$

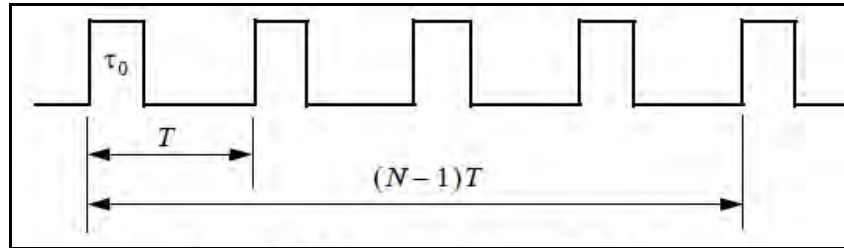


Figure 36. Coherent Pulse Train, $N=5$ (From [25])

Ambiguity diagrams, which are plots of the ambiguity function over delay and Doppler space, are used to determine waveform properties such as target resolution capability, measurement accuracies of time and frequency and response to clutter. There are 3-D and 2-D diagrams of the ambiguity function. The 2-D plot of the 3-D ambiguity diagram that is intersected at a specific threshold is called the ambiguity contour [15]. The obtained two-dimensional plots are ellipses. According to these two-dimensional plots, pulses with narrow widths in delay provide better range accuracy than long pulses. On the other hand, the Doppler accuracy depends on the pulse train length when coherent pulse trains are considered (Figure 37). The range accuracy for single pulse waveforms depends on the pulsewidth as it does in coherent pulse trains whereas the Doppler accuracy depends on the inverse of the pulsewidth ($1/\tau_0$). In a two-dimensional ambiguity diagram, the vertical axis represents Doppler frequency and the horizontal axis represents time delay [15], [26].

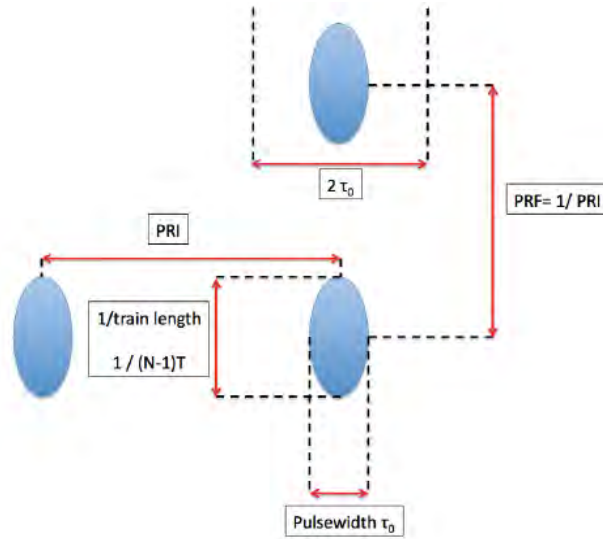


Figure 37. Ambiguity Contour Plot for Coherent Pulse Trains

Extending the two-dimensional ambiguity diagram to three dimensions reveals the amplitude of the general integral shown in Eq. (4.7) or the waveform-specific result shown in Eq. (4.9). The peaks of the three-dimensional ambiguity function along the frequency axis are located at integer multiples of the pulse repetition frequency (PRF) and the peaks along the time delay axis are located at the multiple integer multiples of the pulse repetition interval ($PRI = 1/PRF$). In addition, the width of the peaks along the delay axis is $2\tau_0$ and the width along the Doppler axis is $1/(N-1)T$ [25]. Plots of coherent pulse trains with 15 pulses, PRFs of 30 and 10 kHz, respectively and a constant duty cycle of 20% are provided for a better understanding in Figures 38, 39, 40 and 41. MATLAB codes for creating these figures are provided in *ambiguity_comparison.m* in Appendix B.

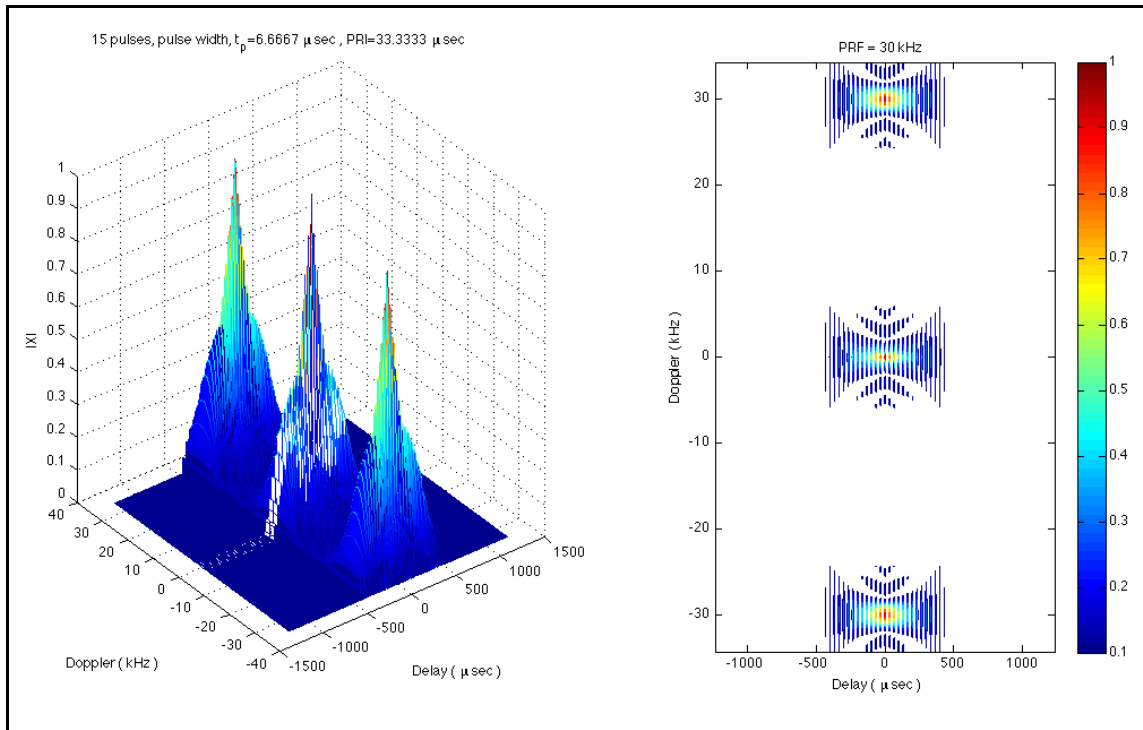


Figure 38. PRF= 30 kHz N=15 Pulses Duty Cycle= 0.2

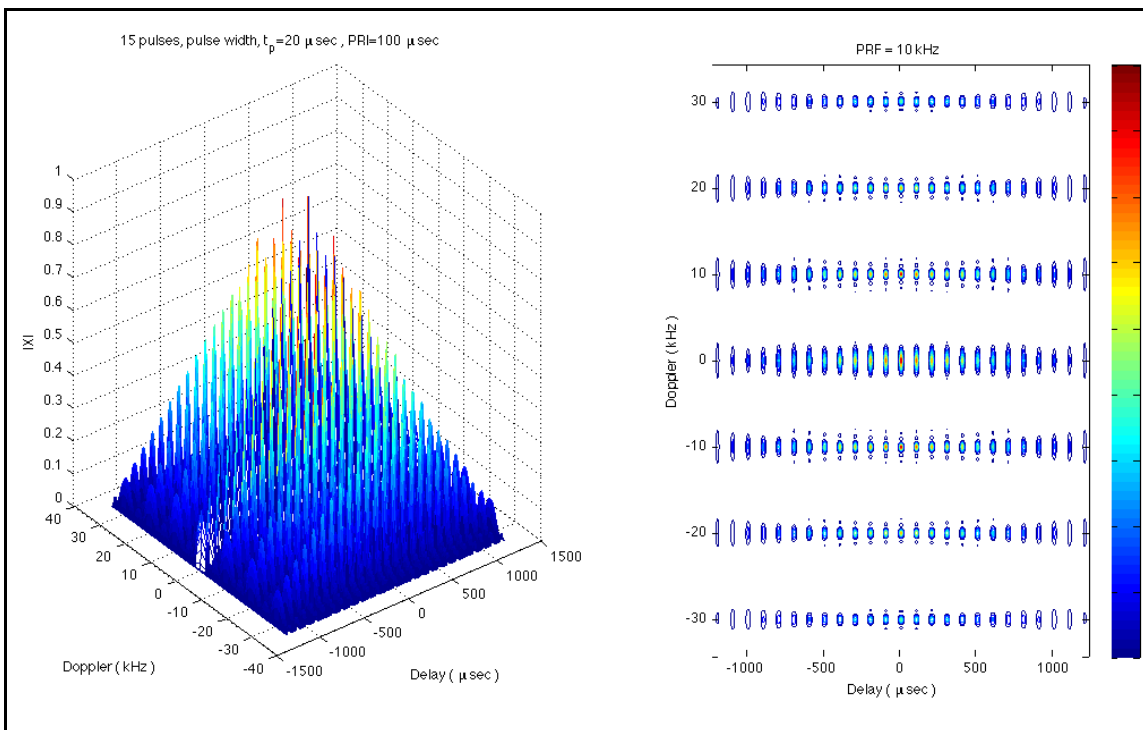


Figure 39. PRF= 10 kHz N=15 Pulses Duty Cycle= 0.2

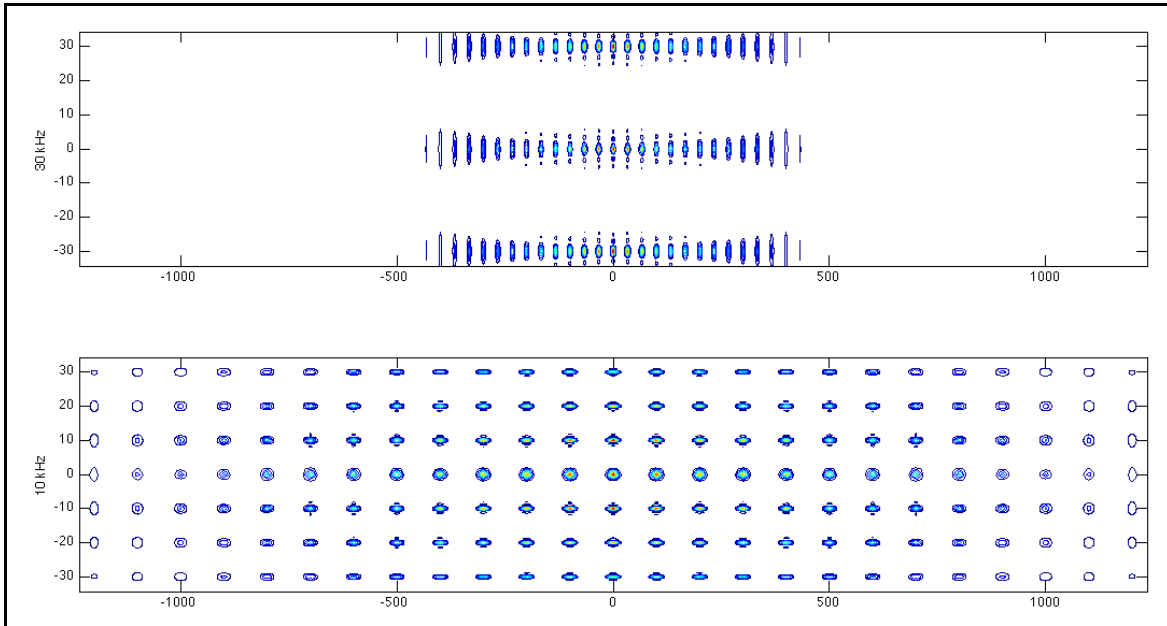


Figure 40. Comparison of Contours for PRF= 30 and 10 kHz

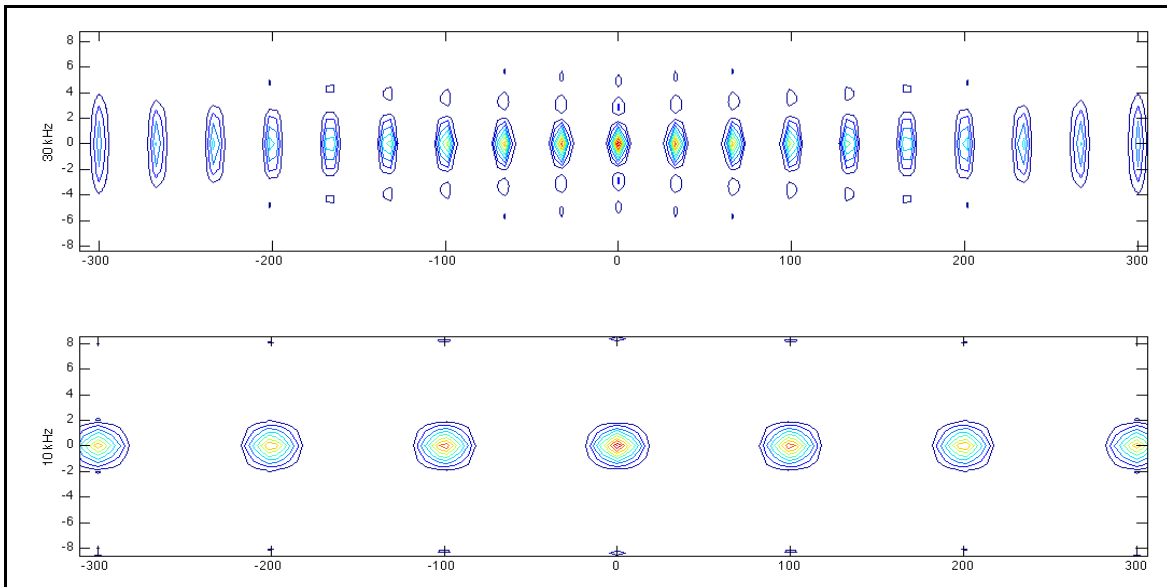


Figure 41. Comparison of Ellipses for PRF= 30 and 10 kHz

As clearly can be seen from Figure 40, decreasing the PRF from 30 kHz to 10 kHz causes the PRI to increase, as they are inversely proportional. Since the horizontal spacing between the ellipses depends on the PRI, we get wider horizontal spacing between ellipses when we use the lower PRF of 10 kHz. For the given PRF values 10 and 30 kHz, the data for 10 kHz is spread 3 times more on the time delay axis when compared to 30 kHz (~1200 μ s vs. ~400 μ s). On the other hand, the opposite condition holds for vertical spacing between the ellipses as it depends on the PRF value. We have wider vertical spacing when we use the higher PRF of 30 kHz compared to 10 kHz.

A constant duty cycle of 0.2 is used throughout all the previous examples, so the pulsewidth is changed accordingly as the PRF changes in order to keep the duty cycle constant. For the given example, we have a larger pulsewidth for 10 kHz (20 μ s) than for 30 kHz (6.67 μ s). As mentioned before, the range accuracy in coherent pulse trains depends on the pulsewidth. Examining Figure 41, we can see that for a given constant duty cycle, the width of the ellipses for 10 kHz are larger than for 30 kHz depending on the varying pulsewidth. Thus, higher PRF provides a better range accuracy for this case as it has a narrower pulsewidth. On the other hand, Doppler accuracy for a coherent pulse train depends on the inverse of train length $[1/(N-1)T]$. Since higher PRFs have lower pulse repetition intervals, they have smaller pulse train lengths. Using the formula for the inverse of train length, we obtain longer lengths on the vertical axis for higher PRFs. Consequently, 10 kHz provides better Doppler accuracy than 30 kHz for the given conditions in the simulation, as is shown in Figure 41.

C. SIMULATION PART I: MODEL WITHOUT CLUTTER

1. Simulation Part I Parameters

A simulation of the 10 GHz radar used for this study in the absence of clutter consisted of the following parameters:

Simulation Part I Parameters	
PRFs	Eight arbitrary medium PRFs for a typical X-band radar: 30, 27, 24, 20, 18, 15, 13 and 10 kHz
Duty Cycle	Constant duty cycle: 20%
Operating Frequency	10 GHz
Velocity Interval	55-1,000 knots (28.3-514.4 m/s)
Doppler Shift	From -34.3 kHz to +34.3 kHz
Range Interval	0–100 nmi (0-185.2 km)
Time Delay	From -1,235 μ s to +1,235 μ s
Number of Pulses	15
PRF Switching	Pulse-to-pulse (time windows equal to PRI)

Table 7. Simulation Part I Parameters

2. Simulation Part I Methodology

The first part of the simulation consists of two separate sections. In the first section, time delays and Doppler frequencies of interest are computed for eight PRFs. After that ambiguity functions are calculated for a pulse train of 15 pulses for each of the eight PRFs. The resulting ambiguity diagrams and contours for each PRF are displayed as an output of the Part I first section simulation work. In the second section of Part I, ambiguity function values of the same PRFs, which start from zero time delay, are combined together based on a pulse-to-pulse switching method. The sequence of the combined PRFs for Section 2 is ordered from high to low because lower PRFs provide longer unambiguous ranges. As mentioned before, medium PRF design is a compromise between low and high PRF designs. Although medium PRFs have both range and Doppler ambiguities, using multiple PRFs can mitigate this inherent problem. It must be noted that the diagrams of each PRF agree only in one location—at the origin of the ambiguity function—which corresponds to the true target location [26]. The output plots

provided in the analysis contain both negative and positive Doppler values on the vertical frequency axis whereas the horizontal axis contains only positive time delays as the ambiguity function has symmetric properties in time delay. The symmetric values that are not shown in these output plots exist for each plot for the negative horizontal axis. The variables that are used in Part I are stored in HALDUN_NO_CLUT.mat at the end of the program. The assumptions, which are to be proven by the evaluation of the results, are:

- Operating with a constant duty cycle minimizes the changes in operating conditions and heating cycles. In order to maintain a constant duty cycle, pulsewidth is changed with regard to the PRF. Since range accuracy depends on the pulsewidth, narrow pulses provide better range accuracy. On the other hand, length of the pulse train, $[1/ (N-1)T]$, determines the Doppler accuracy. Longer pulse trains provide better Doppler accuracy.
- Lower PRFs have longer unambiguous ranges whereas higher PRFs have higher unambiguous velocities.
- It is expected that using multiple medium PRFs with a pulse-to-pulse switching method will be effective until a certain range depending on the PRFs that are used.
- Depending on operational field experience, it is expected that performance results for some medium PRFs will be better than the other medium PRFs that are used.

3. Simulation Part I Plots

The output plots obtained from the simulation for Part I (Figures 42–52) are shown below. MATLAB codes are provided in *no_clut.m* and *no_clut_func.m* in Appendix C.

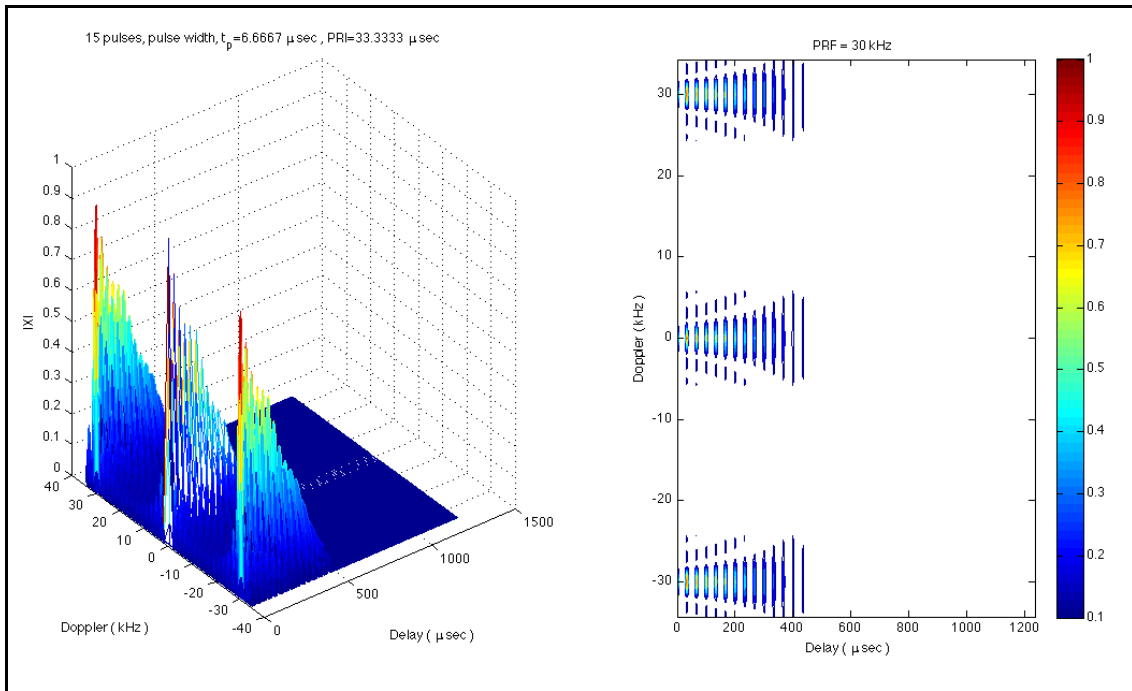


Figure 42. Ambiguity Diagram, N=15 Pulses, PRF= 30 kHz

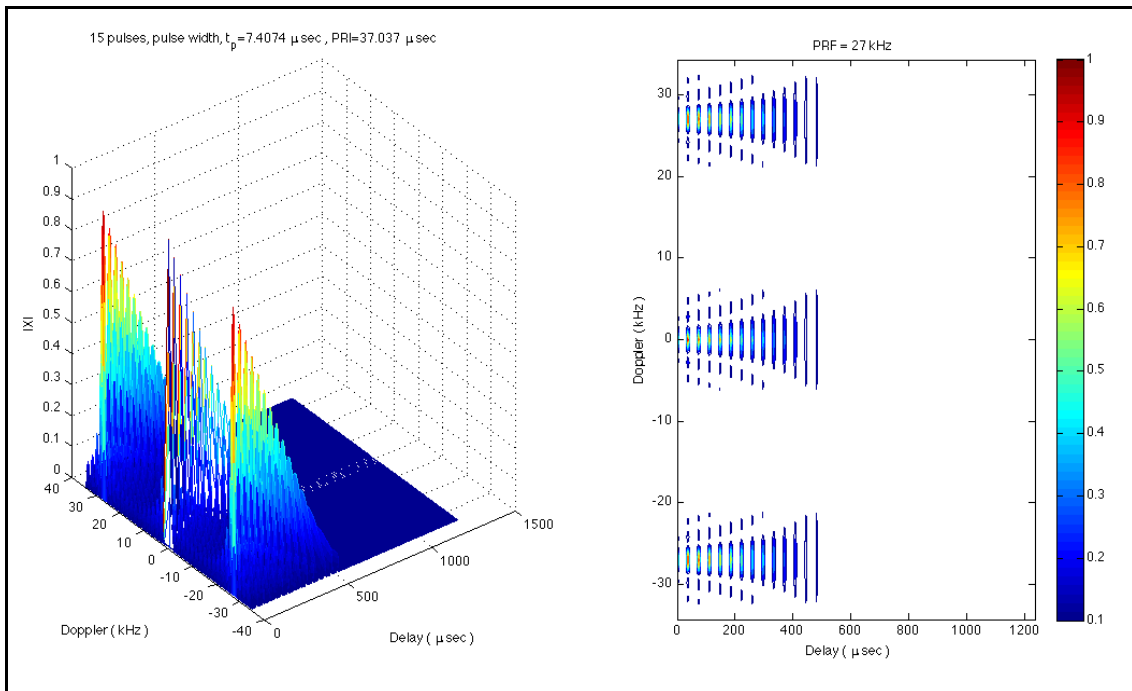


Figure 43. Ambiguity Diagram, N=15 Pulses, PRF= 27 kHz

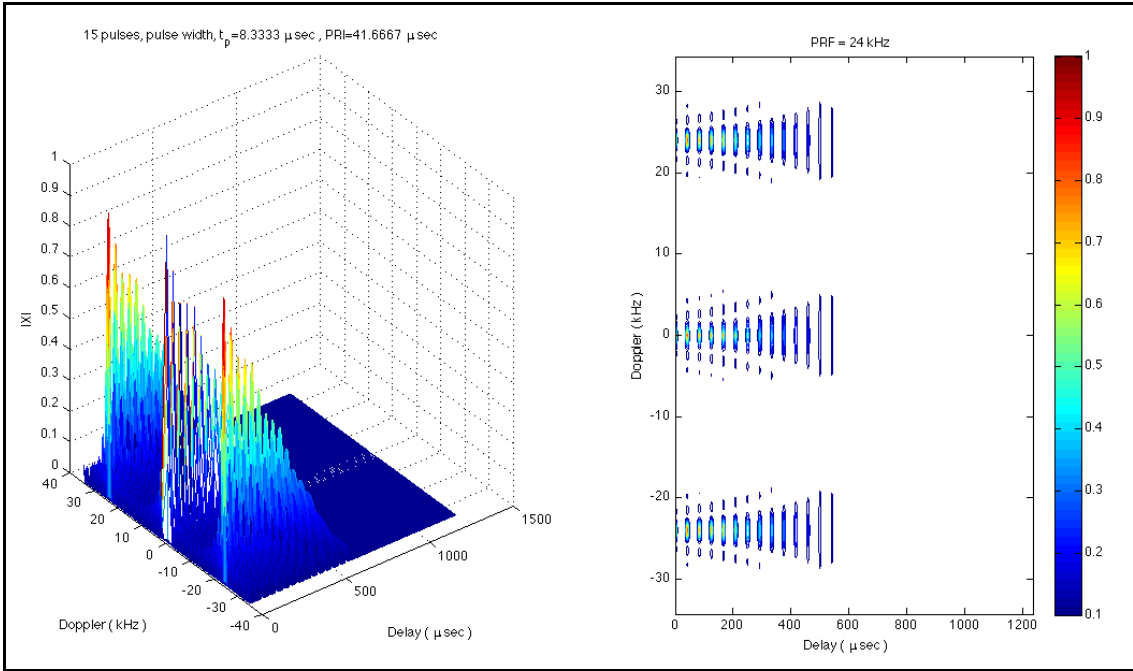


Figure 44. Ambiguity Diagram, N=15 Pulses, PRF= 24 kHz

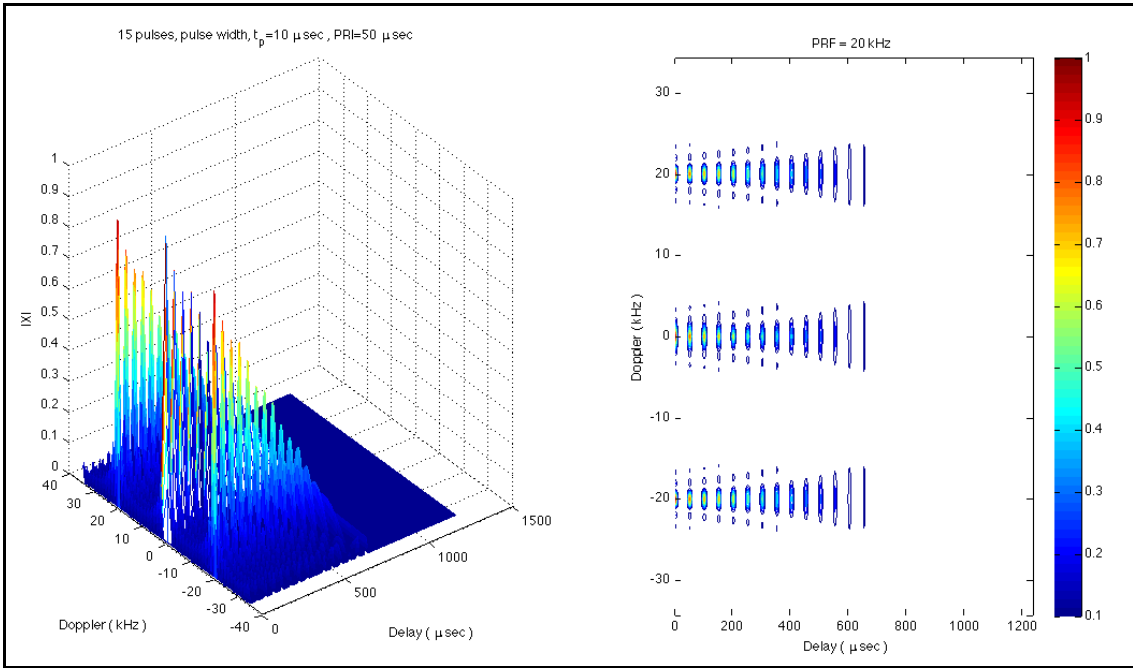


Figure 45. Ambiguity Diagram, N=15 Pulses, PRF= 20 kHz

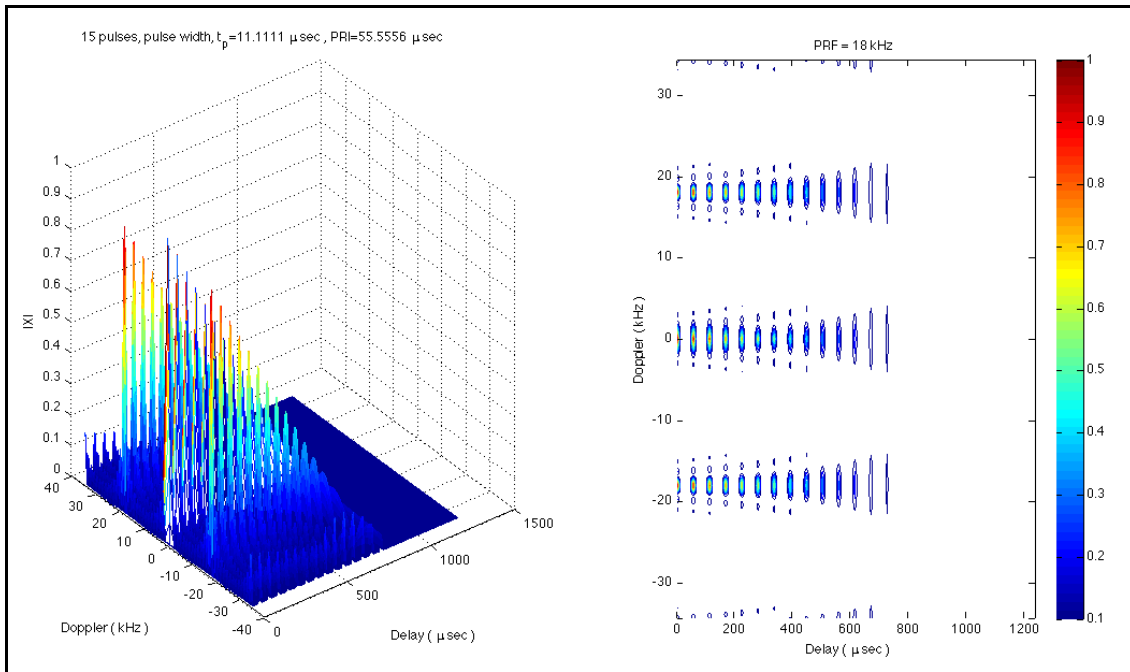


Figure 46. Ambiguity Diagram, N=15 Pulses, PRF= 18 kHz

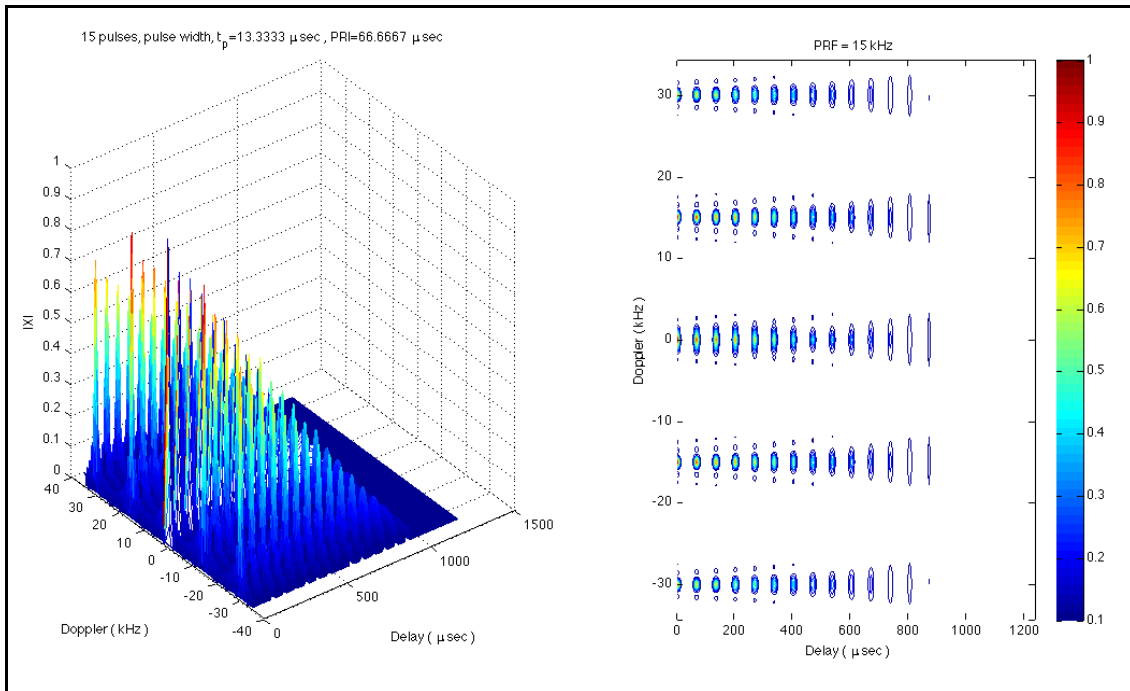


Figure 47. Ambiguity Diagram, N=15 Pulses, PRF= 15 kHz

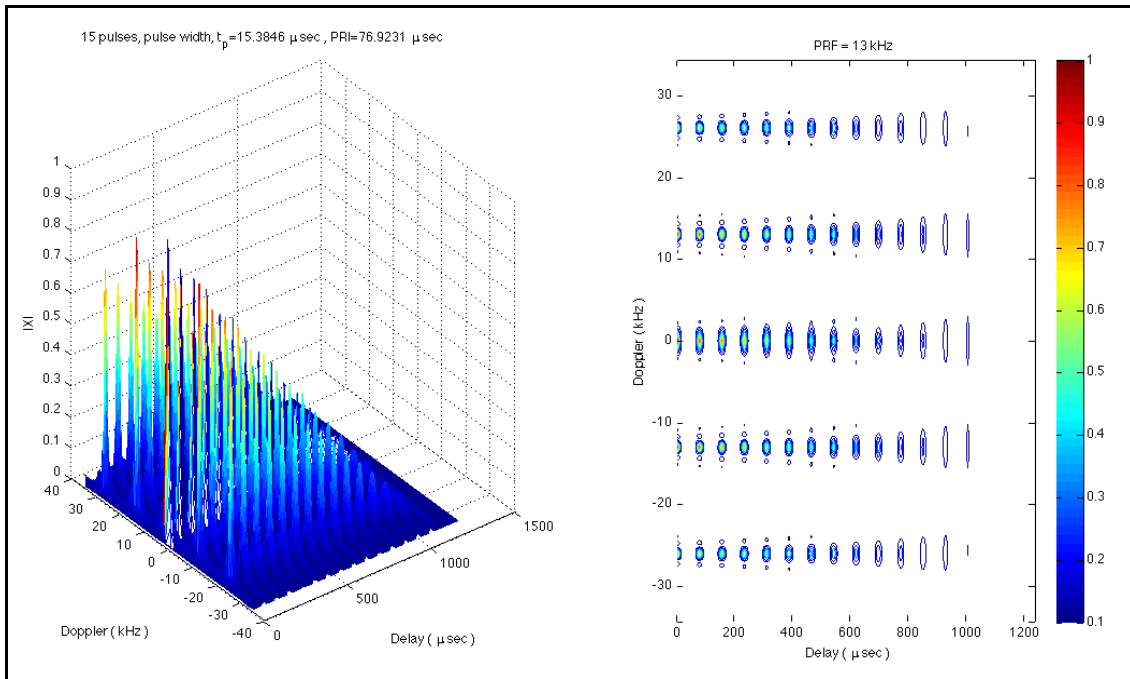


Figure 48. Ambiguity Diagram, N=15 Pulses, PRF= 13 kHz

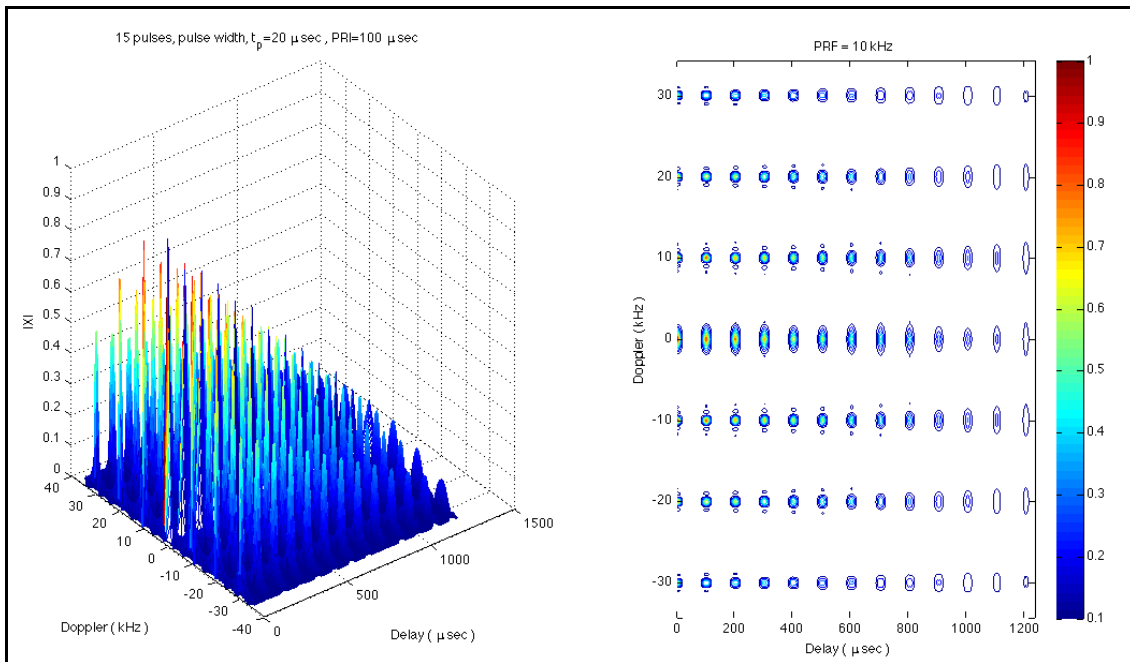


Figure 49. Ambiguity Diagram, N=15 Pulses, PRF= 10 kHz

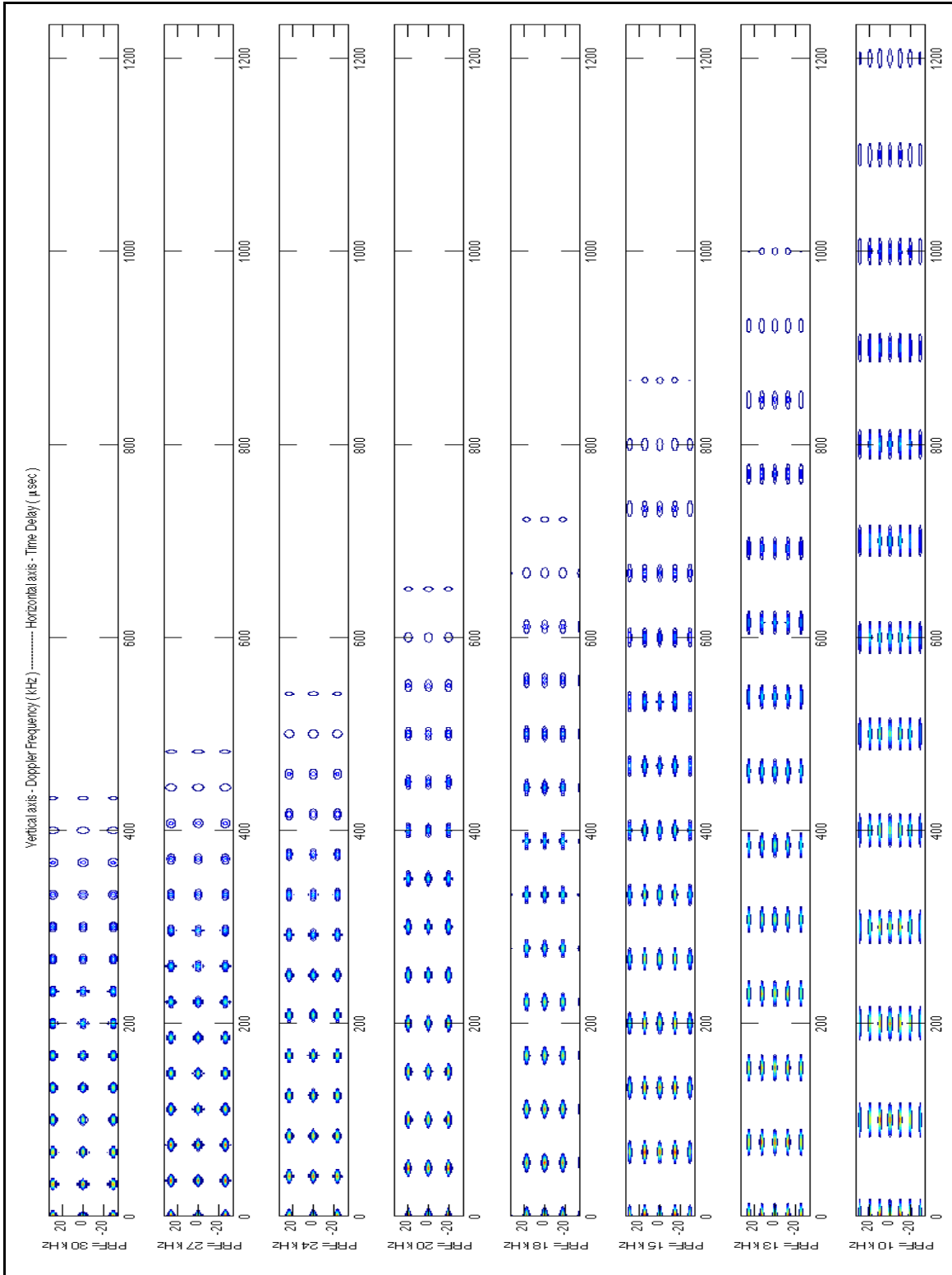


Figure 50. Comparison of Ambiguity Diagrams, N=15 Pulses, 8 Medium PRFs

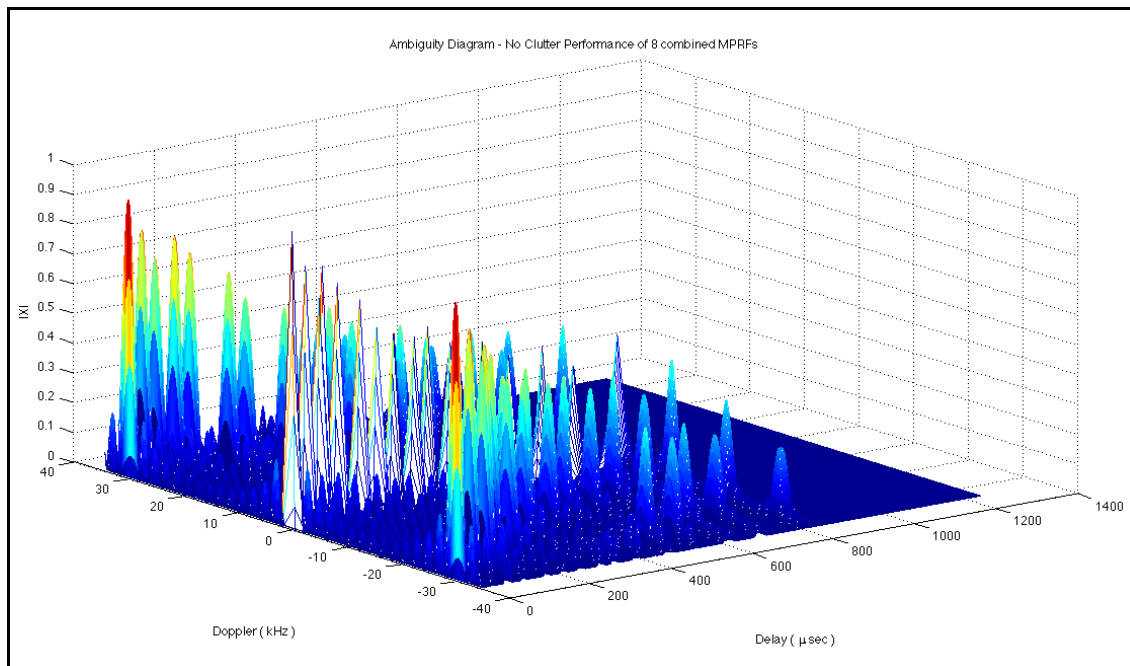


Figure 51. Ambiguity Diagram, N=15 Pulses, Combination of 8 Medium PRFs, No-Clutter Performance

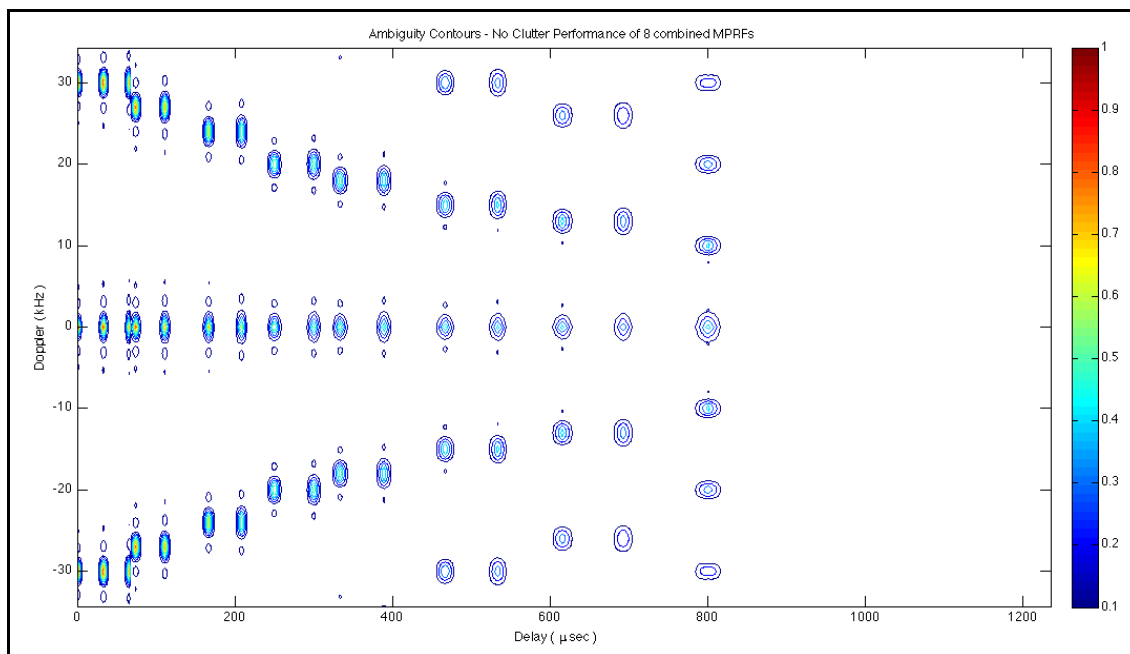


Figure 52. Ambiguity Contours, N=15 Pulses, Combination of 8 Medium PRFs, No-Clutter Performance

4. Simulation Part I Conclusions

When we examine the output plots of the first part of the simulation (Figures 42 through 52), we can conclude that

- Medium PRFs have both range and Doppler ambiguities.
- Using multiple PRFs (Figure 52) can mitigate ambiguities in both domains when compared to using a single PRF (Figure 50).
- Higher PRFs have higher unambiguous velocity whereas lower PRFs have longer unambiguous ranges. As an example, considering a PRF of 30 kHz and a time delay of 400 μs (corresponding to a range of 33 nmi or 60 km), the Doppler shift variation is approximately ± 5.6 kHz, which corresponds to a velocity variation of ± 84 m/s or ± 163 knots (Figure 42). On the other hand, for a PRF of 10 kHz and a time delay of 400 μs , the Doppler shift variation is approximately ± 1.6 kHz, corresponding to a velocity variation of ± 24 m/s or ± 47 knots (Figure 49). Equivalently, the time delay variation for a PRF of 10 kHz and 400 μs time delay is approximately ± 15 μs corresponding to a range variation of ± 1.2 nmi or ± 2.25 km (Figure 49). The variations in time delay and in range are ± 3 μs and ± 0.25 nmi (450m), respectively for a PRF of 30 kHz and time delay of 400 μs (Figure 42).

	PRF= 30 kHz Time Delay= 400 μs	PRF= 10 kHz Time Delay= 400 μs
Time Delay Variation	± 3 μs	± 15 μs
Range Variation	± 0.25 nmi	± 1.2 nmi
Doppler Shift Variation	± 5.6 kHz	± 1.6 kHz
Velocity Variation	± 163 knots	± 47 knots

Table 8. Parameter Variations for 30 and 10 kHz

- Based on maintaining a constant duty cycle, lower PRFs result in wider pulses, which decrease range accuracy due to longer pulsewidths whereas higher PRFs result in shorter pulse repetition intervals, which cause a decrease in Doppler accuracy. On the other hand, longer pulse trains, based on the aggregate number of pulses transmitted, provide better

Doppler accuracy. Target illumination time (dwell time) must be sufficient to transmit all of the pulses. Consequently, despite the fact that lower PRFs provide longer unambiguous ranges and higher PRFs provide higher unambiguous velocities, using too low or too high PRFs will result in poor range and Doppler accuracies, respectively. Thus, using multiple medium PRFs approximately around 20 kHz will provide moderate ambiguities and accuracies in both time and frequency domains and is considered to be a good overall performer when considering both range and Doppler.

- Regardless of the PRF being used, all ambiguity diagrams agree only at the origin, which is where the true target is located.
- The accuracy of the Doppler increases as the number of pulses in the pulse train increases.
- According to Figure 52, when multiple PRFs are used in order to overcome ambiguities, we can see that ambiguities in frequency domain change less than they do in time domain after the time delay of approximately 600 micro seconds, which corresponds to 48.6 nmi. We can conclude that when the radar is configured as described for this evaluation, approximately 50 nautical miles is the effective range for multiple medium PRFs considering ambiguities in both domains.

D. CLUTTER

Clutter is an interference signal, but from the radar perspective it is part of the received backscatter signal. Clutter can take many forms, with the most common caused by natural scatterers such as land, sea and weather echoes. Clutter and noise have some important differences, two of which are the power spectrum (i.e., the areas in the spectrum where clutter returns have their strongest content) and the dependence of clutter on radar parameters such as the transmitted power, antenna gain and the range of the radar to the terrain [26].

Considering the clutter from the earth's surface, the footprint model that is obtained when the aircraft illuminates the ground is shown in Figure 53, where γ is the depression angle, ψ is the grazing angle and R is the slant range [16].

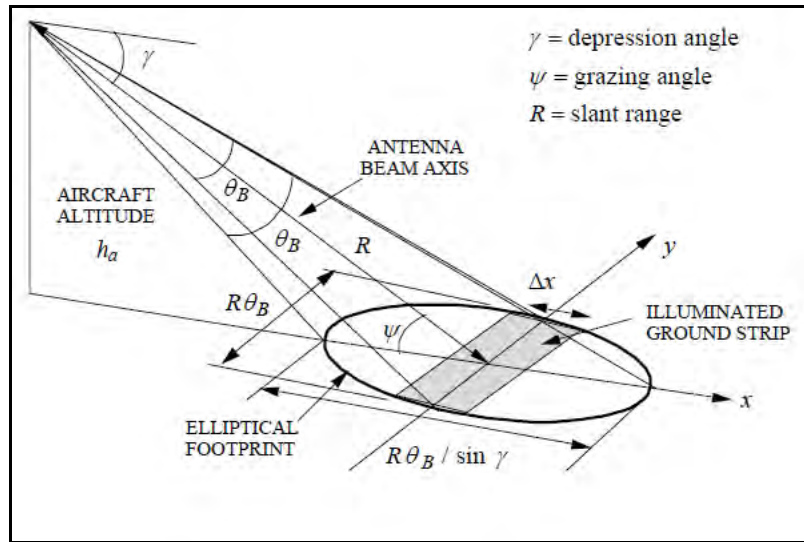


Figure 53. Footprint for Surface Clutter (From [16])

Although the actual illumination ground strip is curved, it is almost rectangular as long as the conditions include a long slant range and a small beamwidth. This simple model supports calculation of the relative power received from a target backscatter to that which is received from the clutter (signal-to-clutter ratio). There are two different cases in calculating signal-to-clutter ratio (SCR). One of them is the beamwidth limited case and the other is the pulsewidth limited case. Considering that $ct/2$ is the pulse extent as a radar signal propagates in space and Δ is the illumination strip (length and width) on the ground, the case is beamwidth-limited if the entire footprint is illuminated whereas it is pulsewidth-limited if only a portion of the elliptical footprint is illuminated. A simple diagram (Figure 54) and the formula for the calculation of the illumination strip are provided below.

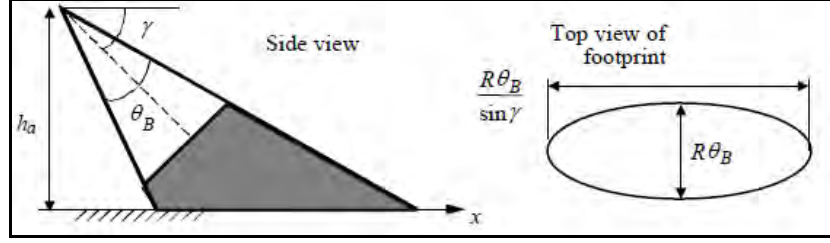


Figure 56. Beamwidth-Limited Case (From [16])

In the simulation, a beamwidth-limited case is assumed, as is typically expected for highly-directive narrow beamwidth radar antennas. The clutter area for the footprint ellipse is,

$$A_c = \frac{\pi}{4} (R\theta_B) \left(\frac{R\theta_B}{\sin\gamma} \right) = \frac{\pi (R\theta_B)^2}{4 \sin\gamma} \quad (4.12)$$

The equation for the clutter power and the SCR are shown in Eq.(4.13) and Eq.(4.14), respectively [16].

$$C = \frac{P_t G_t A_e \sigma^0 A_c}{(4\pi)^2 R^4} \quad (4.13)$$

$$SCR = \frac{S}{C} = \frac{\sigma_T}{\sigma^0 A_c} \quad (4.14)$$

The backscattering coefficient, σ^0 , varies with the grazing angle, frequency and environmental conditions, but for this simulation an average value of -28.8 dB is used to represent X-band, agricultural terrain with slopes exceeding 2 degrees, which is also consistent with the conditions that are present in the area of interest, Turkey [8]. Graphs of signal-to-clutter ratio (SCR) for the beamwidth limited case [Eq. (4.14)] are plotted versus height in ft (Figure 57), target radar cross section in m^2 (Figure 58) and beamwidth in degrees (Figure 59) under the specific conditions stated in “Simulation Part II Parameters (Table 9).” In addition, another graph is shown in Figure 60 where the relation between the grazing angle and the distance are shown for the simulation parameters. In Figure 57, the change in SCR is plotted versus the varying altitude between 0 and approximately 10,000 feet, assuming a constant target arrival angle of near-grazing (90^0), target radar cross section of $5 m^2$, backscatter coefficient of -28.8 dB

and beamwidth of 3.3° . We can see that after approximately 4,000 feet, the clutter power exceeds the signal power under the given circumstances.

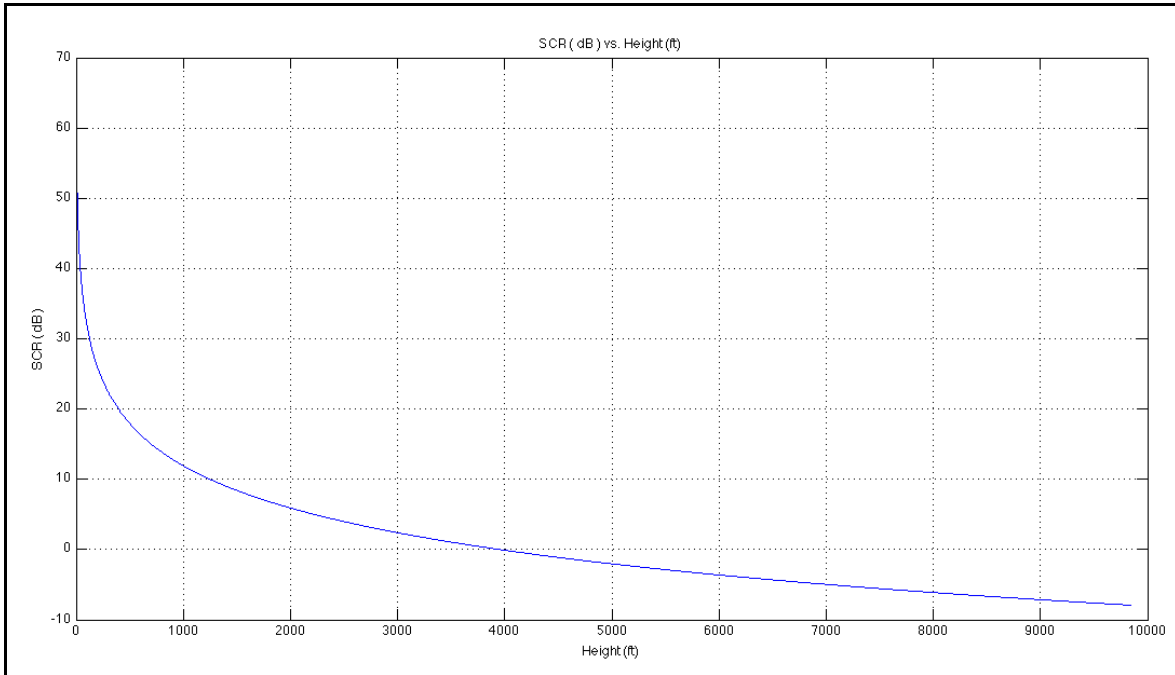


Figure 57. SCR (dB) Vs. Height (ft)

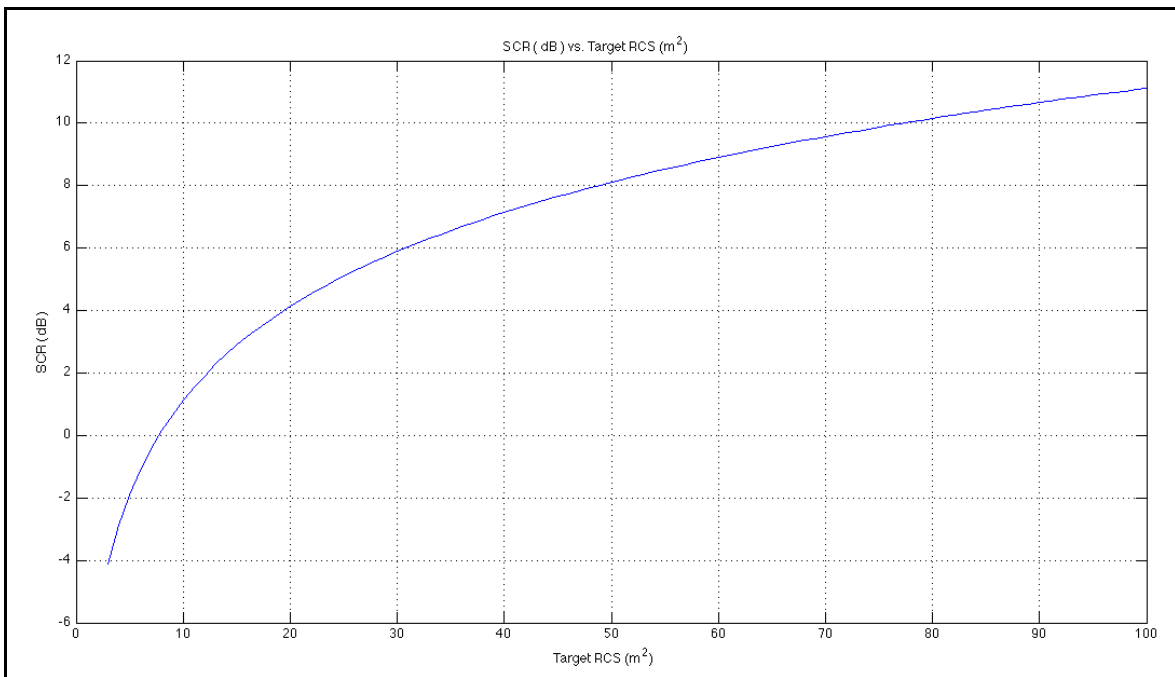


Figure 58. SCR (dB) Vs. Target RCS (m²)

Likewise, SCR is plotted versus the varying target radar cross section between 3 and 100 m² in Figure 58, assuming a constant grazing angle of 90⁰, altitude of approximately 5,000 feet, backscatter coefficient of -28.8 dB and beamwidth of 3.3⁰. We can see that the signal power exceeds the clutter power after approximately 8 m² target cross section under the given circumstances.

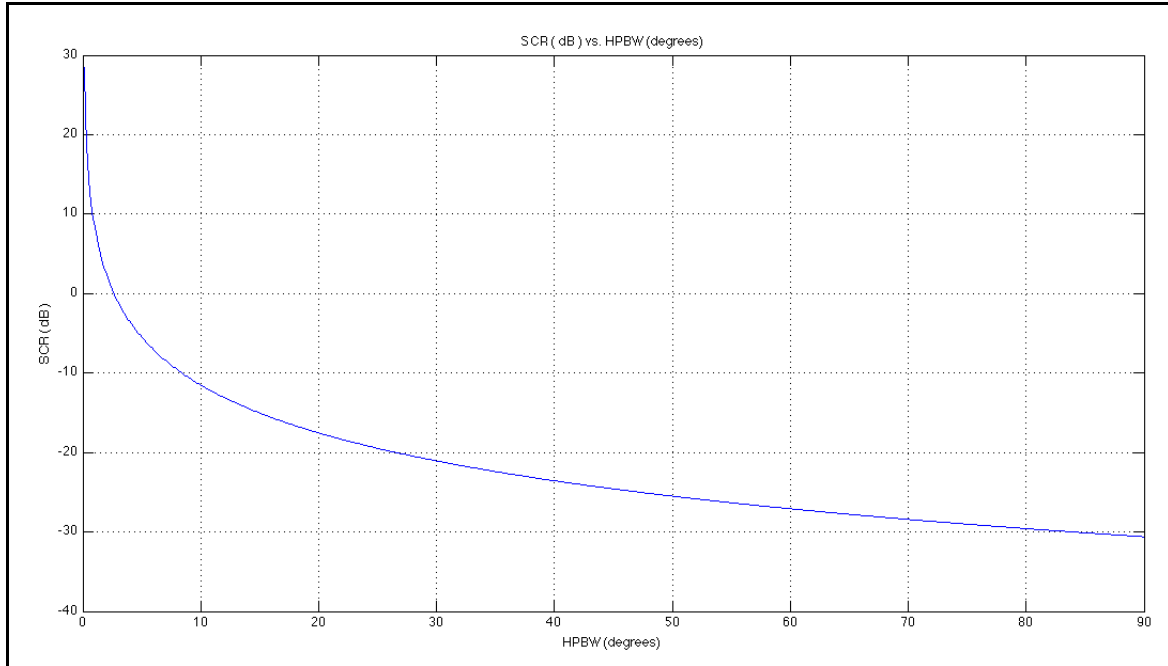


Figure 59. SCR (dB) Vs. HPBW (degrees)

SCR is plotted versus the varying half-power beamwidth between 0 and 90⁰ in Figure 59, assuming a constant target arrival angle of near-grazing (90⁰), altitude of approximately 5,000 feet, backscatter coefficient of -28.8 dB and target radar cross section of 5 m². We can see that the clutter power exceeds the signal power for half-power beamwidths exceeding approximately 4⁰ under the given baseline conditions. In addition, the change in the distance versus varying grazing angle between 0 and 90⁰ is plotted in Figure 60, assuming a constant altitude of approximately 9,800 feet, backscatter coefficient of -28.8 dB, beamwidth of 3.30 and target radar cross section of 5 m². We can see that the decrease in the grazing angle does not have a significant effect on the distance down to approximately 10⁰, whereas the decrease in the grazing angle after approximately 10⁰ increases the distance significantly under given circumstances.

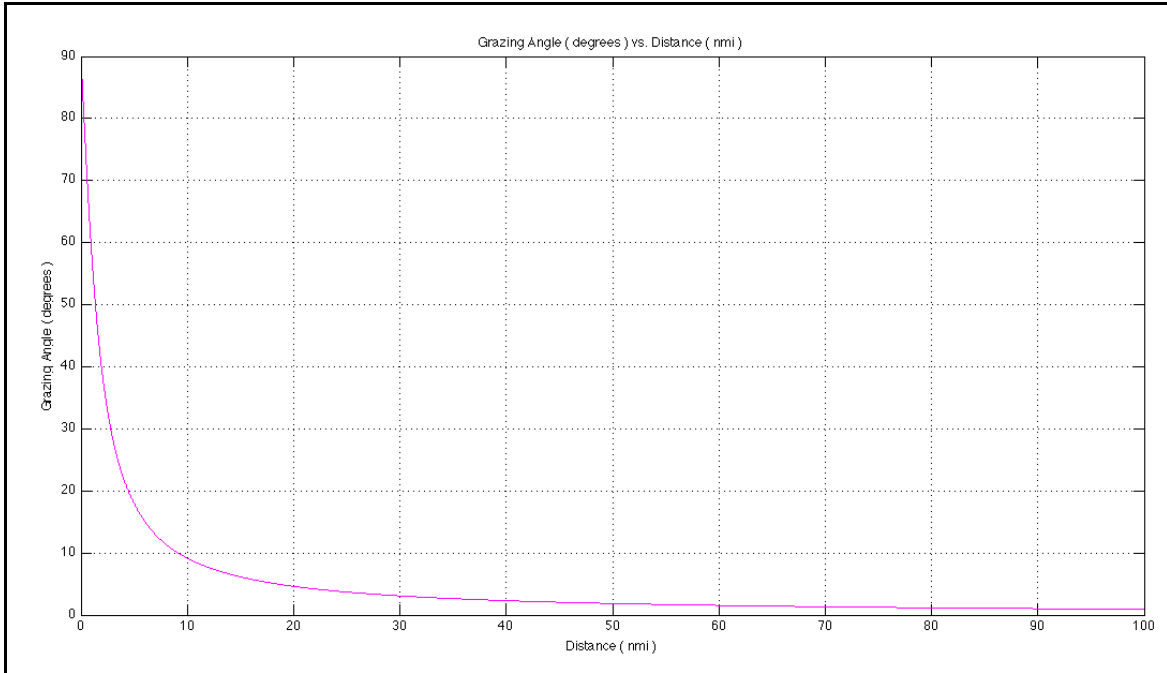


Figure 60. Grazing Angle (degrees) Vs. Distance (nmi)

MATLAB codes for Figures 57–61 are provided in *SCR_height.m* (Figure 57), *SCR_TRCS.m* (Figure 58), *SCR_HPBW.m* (Figure 59), and *SCR_grz.m* (Figures 60–61) in Appendix D.

E. SIMULATION PART II: MODEL WITH CLUTTER

1. Simulation Part II Parameters

The parameters for the second part of the simulation in addition to the parameters of the first part given in Table 7 are shown in Table 9.

Simulation Part II Parameters	
Target radar cross section	5 m ² (fighter jet)
Backscattering coefficient	-28.8 dB (average)
Altitude	2,744 m (9,000 ft)
Beamwidth	3.3 ⁰

Table 9. Simulation Part II Parameters

2. Simulation Part II Methodology

In this part of the simulation, a clutter model is designed within the given parameters. After the calculation of time delays, Doppler frequencies and the corresponding ambiguity function values, signal-to-clutter ratios (SCR) are calculated. Moreover, SCR in dB is plotted versus time delay in microseconds (μs) and distance in nautical miles (nmi) for demonstration purposes. In this simulation, SCR is only allowed to vary with the distance and the grazing angle. Although the other variables may change in a real-time environment, they are assumed constant throughout this simulation. After a simulation run, the normalized ambiguity values, which are between zero and one, are converted to dB. Negative values of SCR mean that the clutter power is more than the signal power, and clutter significantly reduces the detection performance. Thus, the positive values of SCR are all assumed zero (truncated) because the clutter presence will not be expected to degrade detectability. The negative SCR values, on the other hand, have the potential of reducing detectability significantly. Therefore, negative SCR value results are subtracted from the ambiguity values obtained in Simulation Part I (clutter-free) using dB to represent the clutter impact on the ambiguity function. The results are displayed for each PRF separately, and are compared against the corresponding results without clutter (in the next figure). In the final section, the use of multiple medium PRFs with pulse-to-pulse switching method under clutter conditions is examined. As previously done in the display of Part I data, the plots contain both negative and positive Doppler frequencies on the vertical axis, whereas time delay is only given in positive values on the horizontal axis since the exact values exist on the symmetric negative axis. The variables used in the simulation are saved in HALDUN_CLUT.mat at the end of the program. The assumptions, which are to be proved by the evaluation of the results of this part, are:

- The clutter will not degrade detectability up to a certain distance as there will be a strong positive SCR value, but after transition to a clutter-dominating condition, the SCR will decrease drastically, almost disabling target detection capability after some point (a threshold detection condition will become evident when observing the ambiguity function).
- Real time environment values may differ from the simulation results as many assumptions are made and many variables are kept constant.

- It is assumed that the best performance results will be acquired when PRFs around 20 kHz are used since this was one of the basic findings in the clutter-free runs.

3. Simulation Part II Plots

The plots obtained from the simulation for Part II are shown below. MATLAB codes are provided in *clut.m* and *clut_func.m* (for Figures 62, 64, 66, 68, 70, 72, 74, 76, 78, 80, 82) in Appendix E.

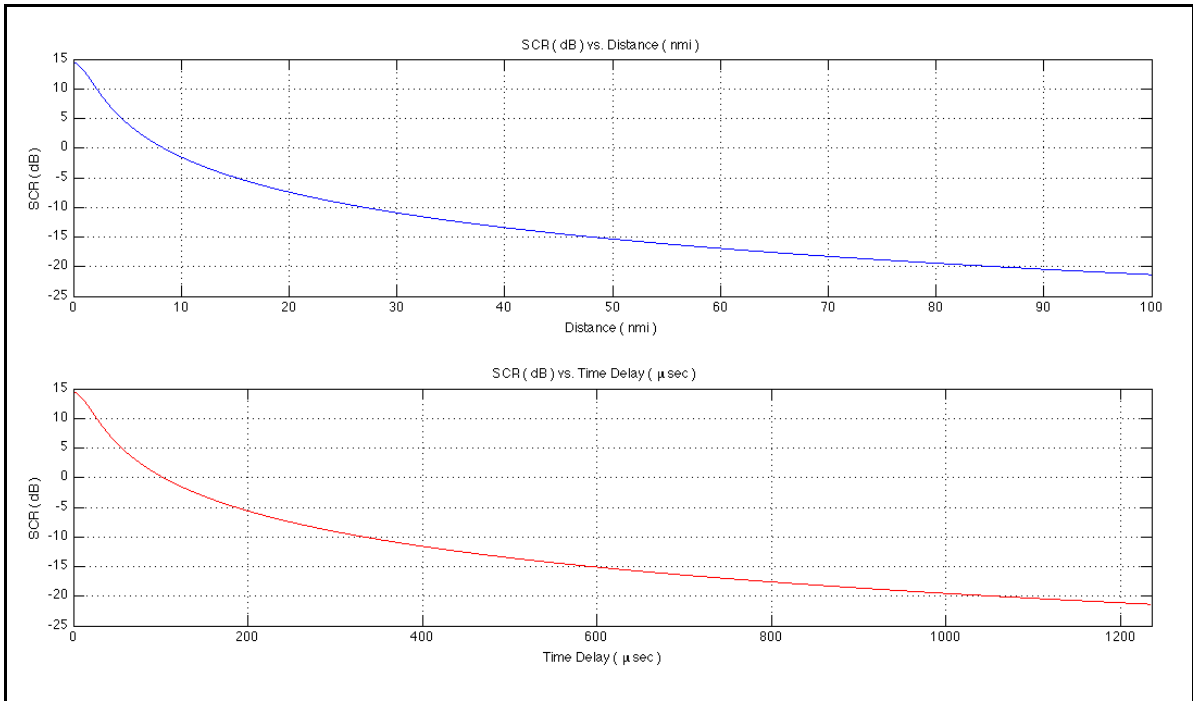


Figure 61. SCR (dB) Vs. Distance (nmi) and Time Delay (μ s)

Figure 61 shows the change in SCR versus the distance and the corresponding time delay under given simulation conditions. We can see that clutter has no effect on the detection capability up to approximately 8 nautical miles (nmi) in this simulation.

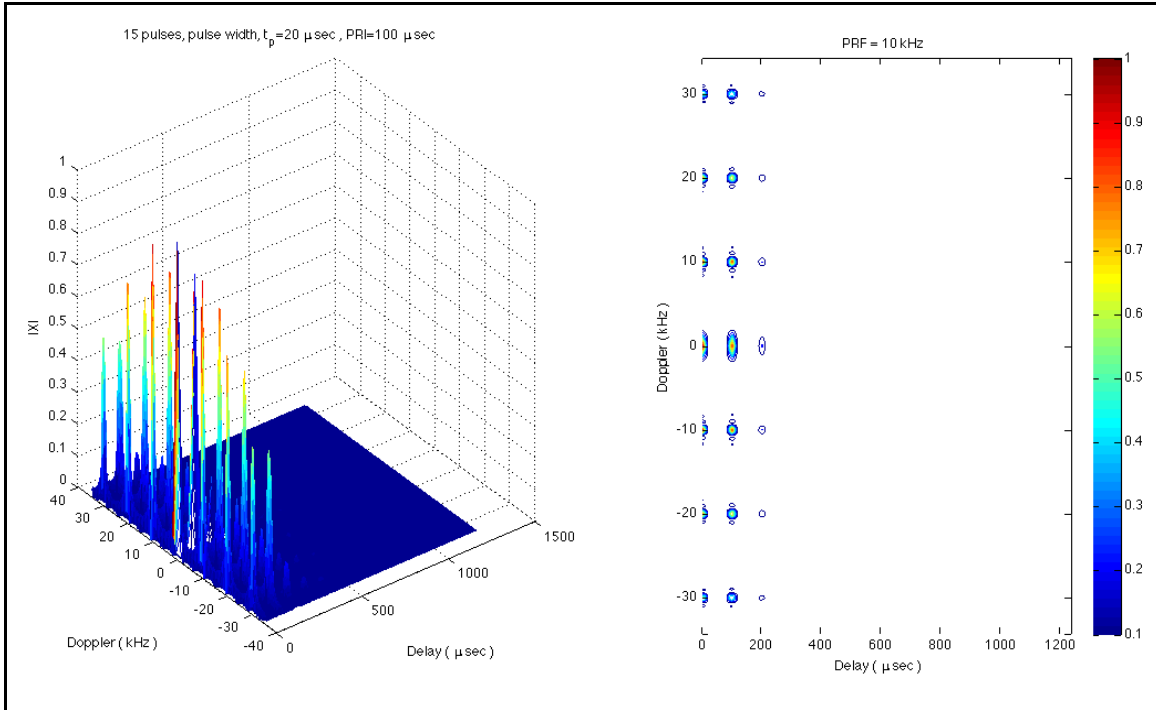


Figure 62. PRF=10 kHz , N=15 Pulses, With Clutter

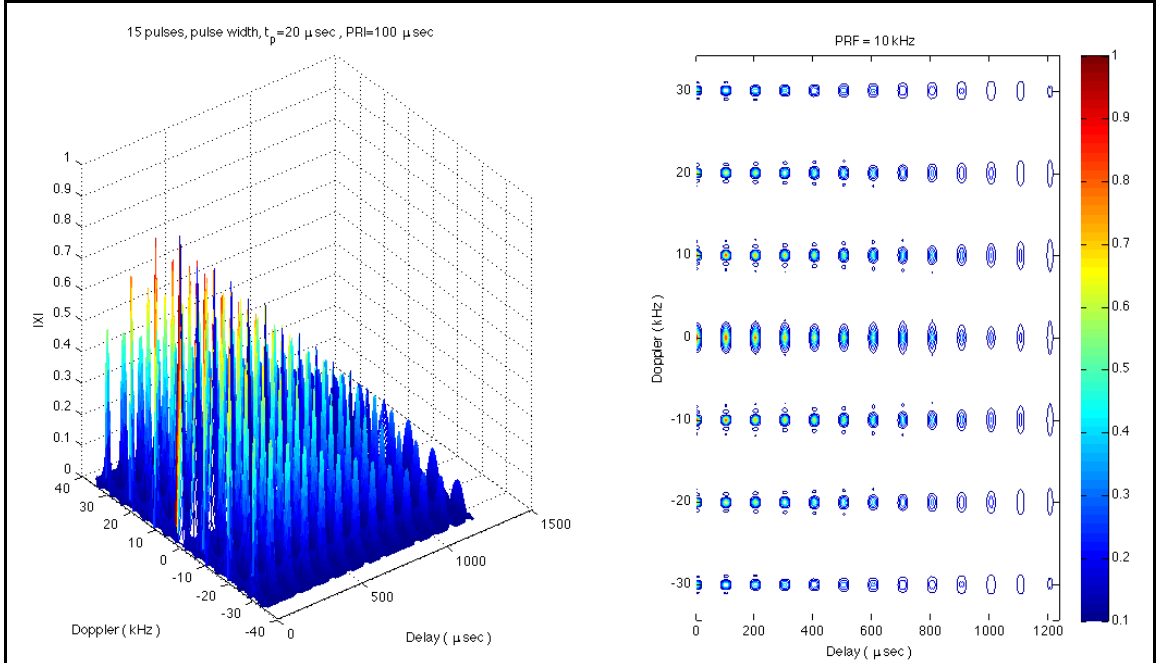


Figure 63. PRF=10 kHz , N=15 Pulses, Without Clutter

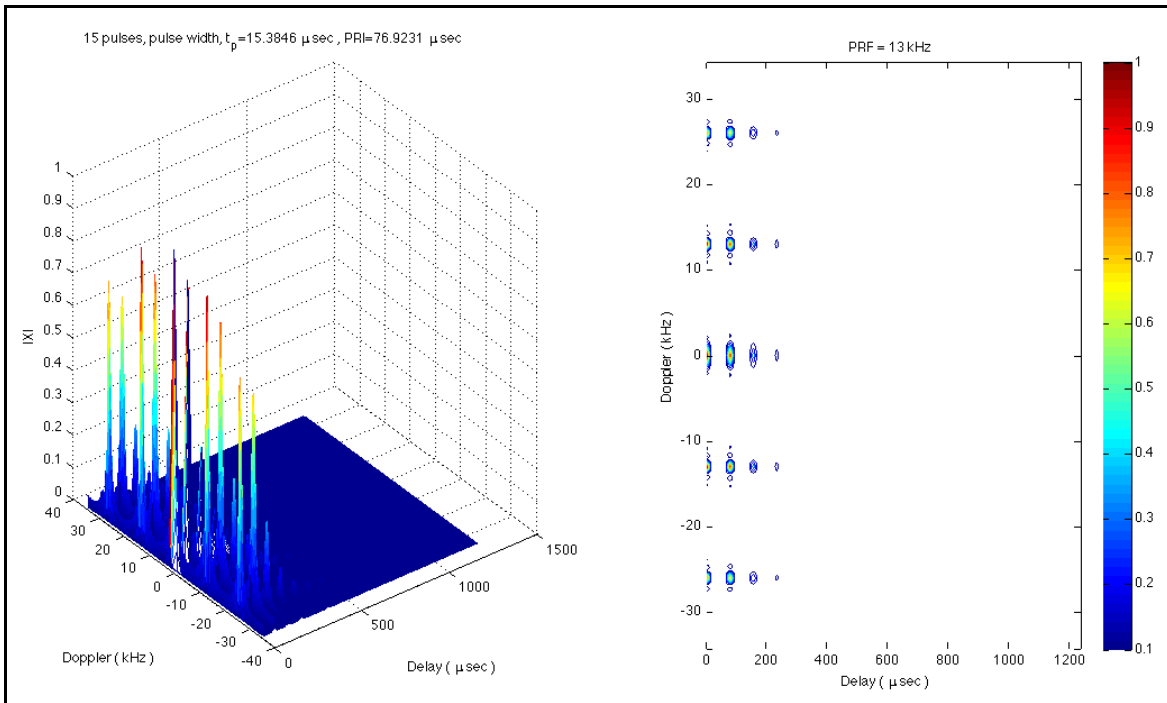


Figure 64. PRF=13 kHz , N=15 Pulses, With Clutter

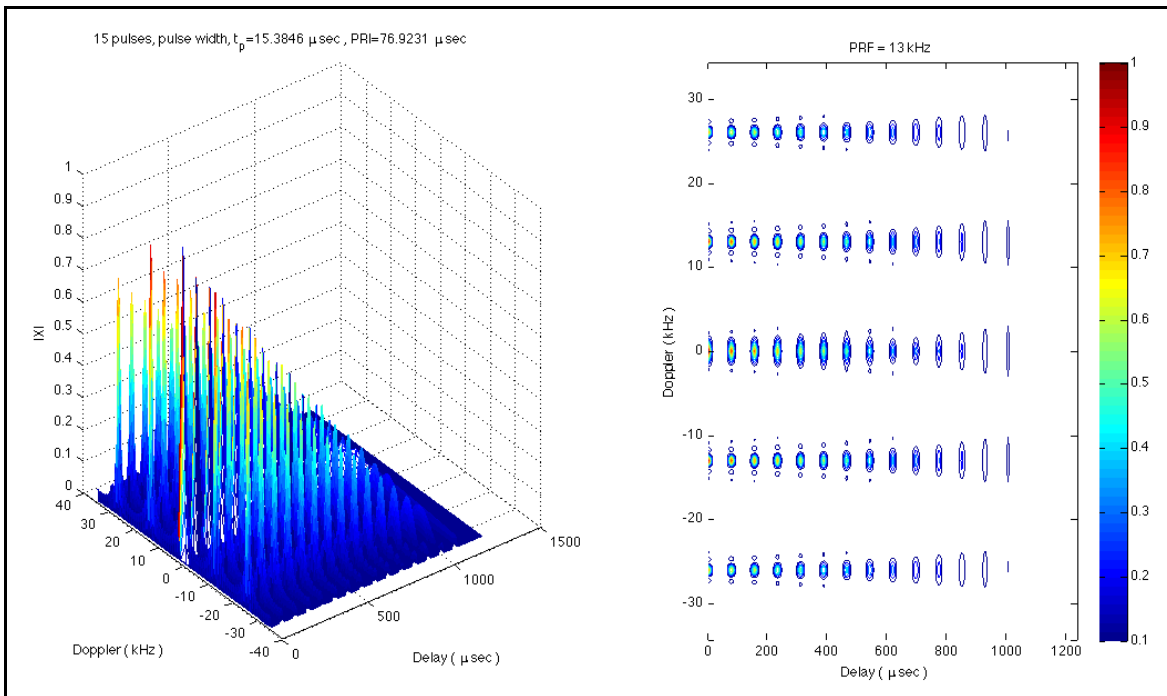


Figure 65. PRF=13 kHz , N=15 Pulses, Without Clutter

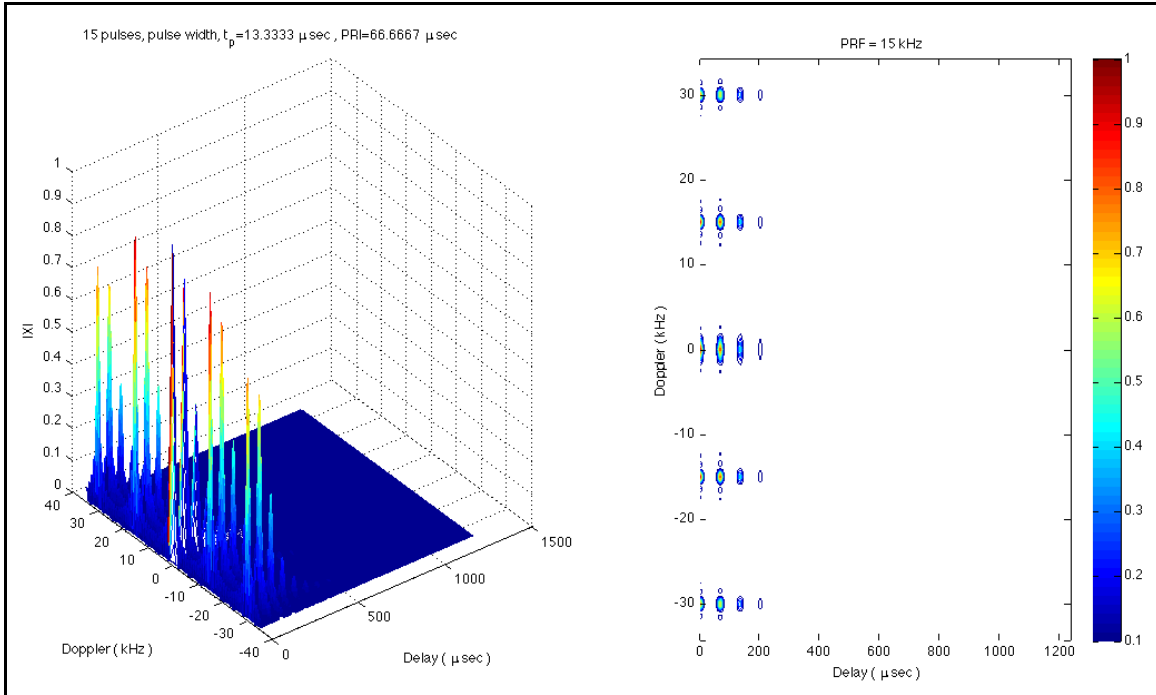


Figure 66. PRF=15 kHz , N=15 Pulses, With Clutter

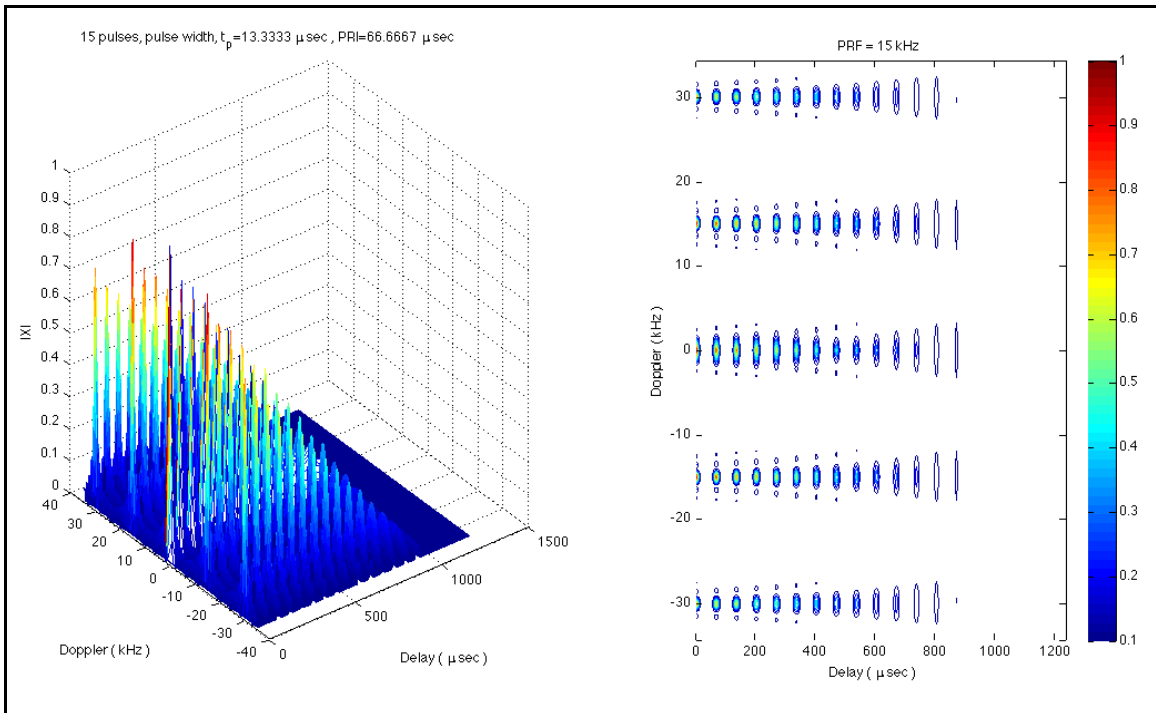


Figure 67. PRF=15 kHz , N=15 Pulses, Without Clutter

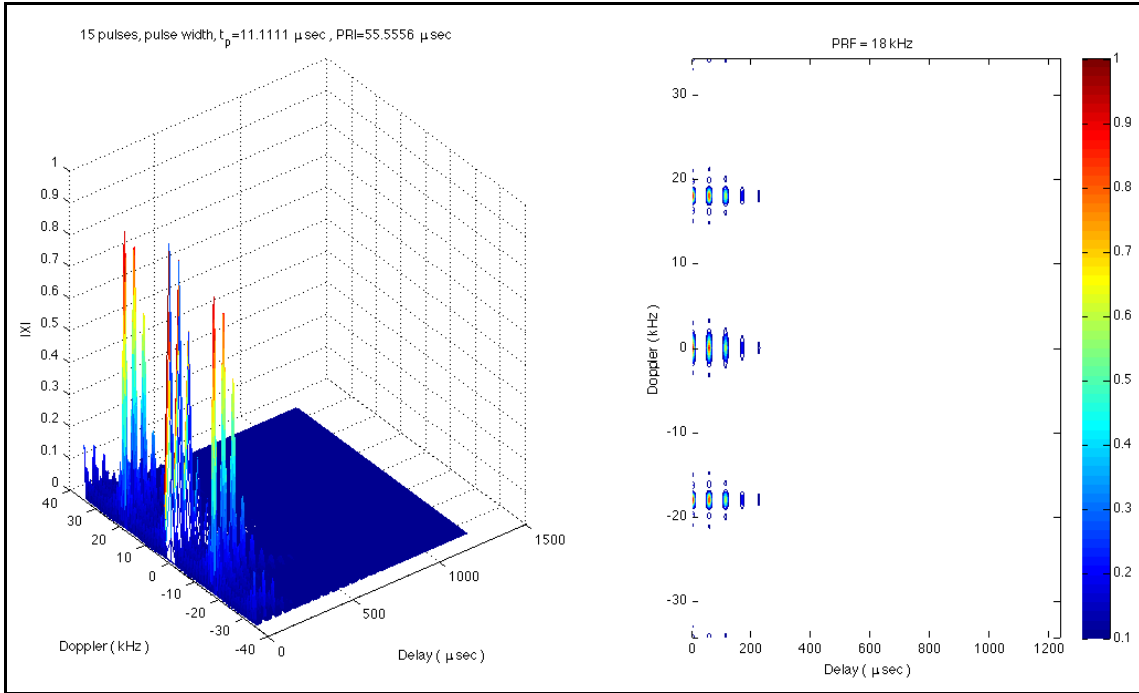


Figure 68. PRF=18 kHz , N=15 Pulses, With Clutter

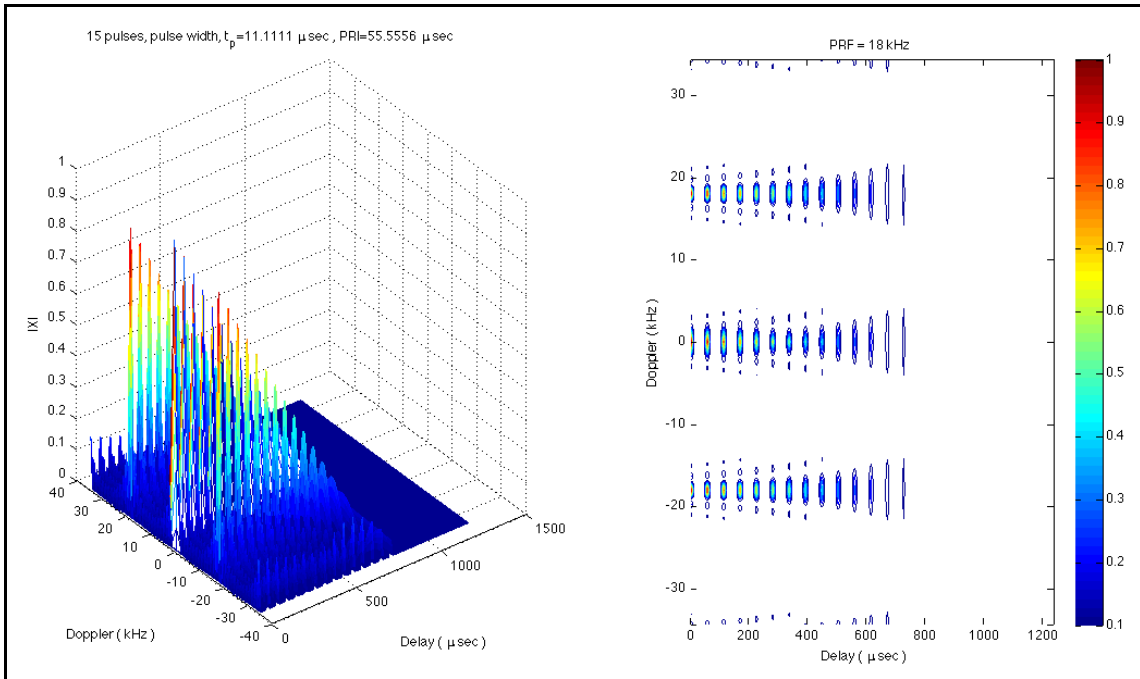


Figure 69. PRF=18 kHz , N=15 Pulses, Without Clutter

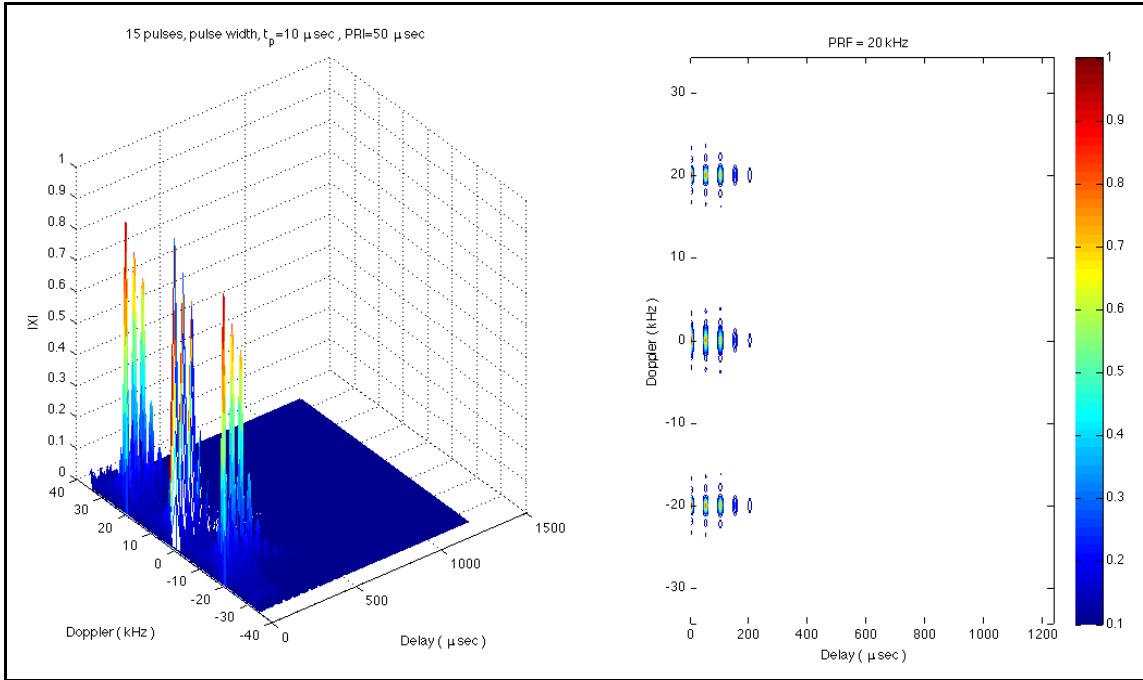


Figure 70. PRF=20 kHz , N=15 Pulses, With Clutter

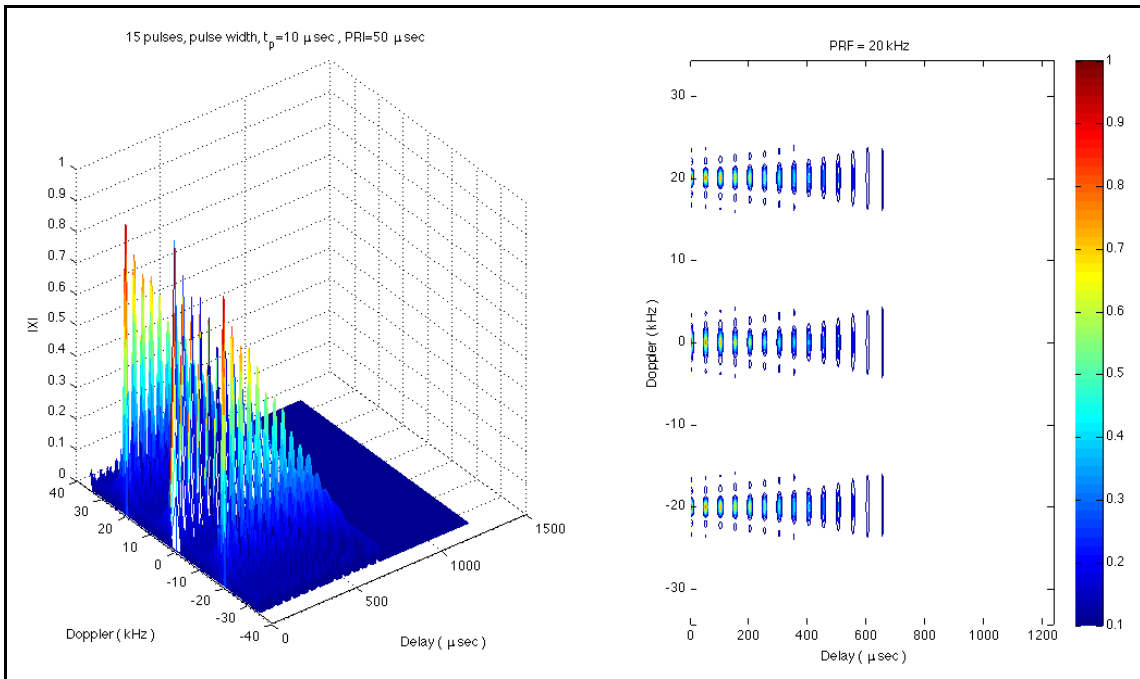


Figure 71. PRF=20 kHz , N=15 Pulses, Without Clutter

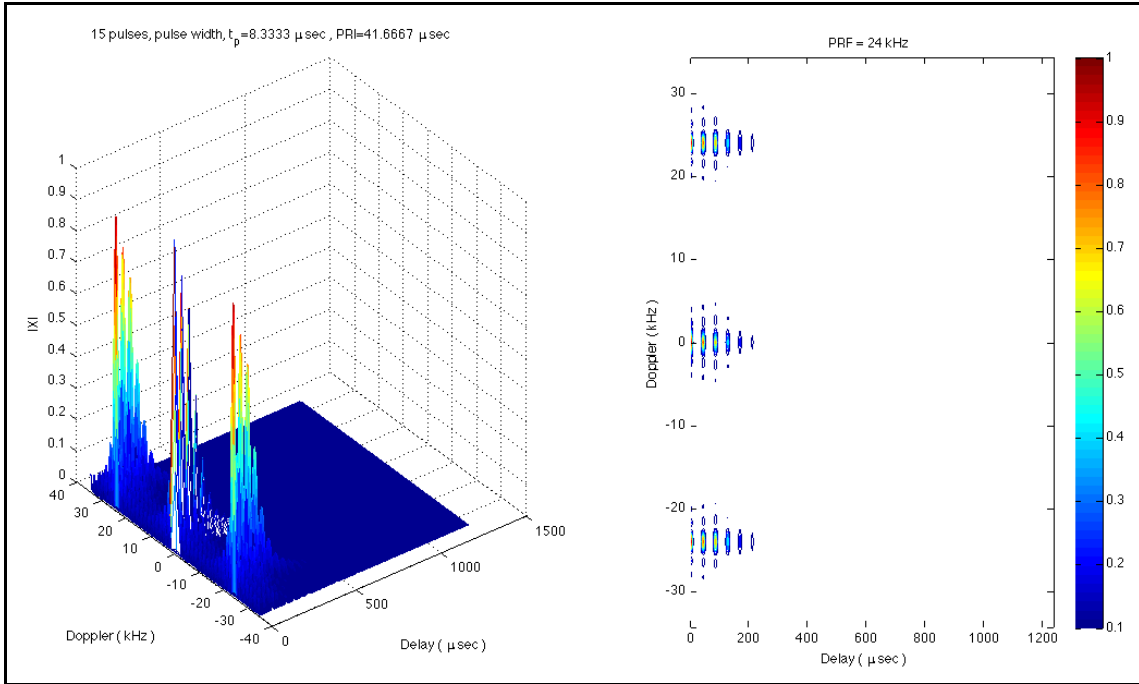


Figure 72. PRF=24 kHz , N=15 Pulses, With Clutter

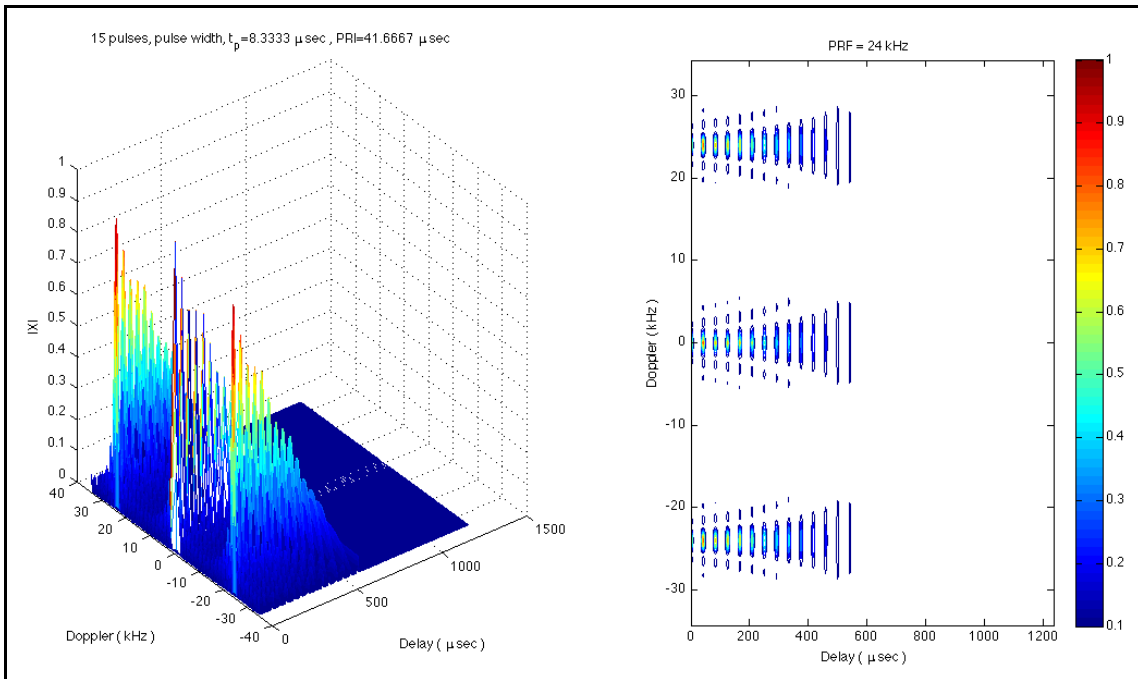


Figure 73. PRF=24 kHz , N=15 Pulses, Without Clutter

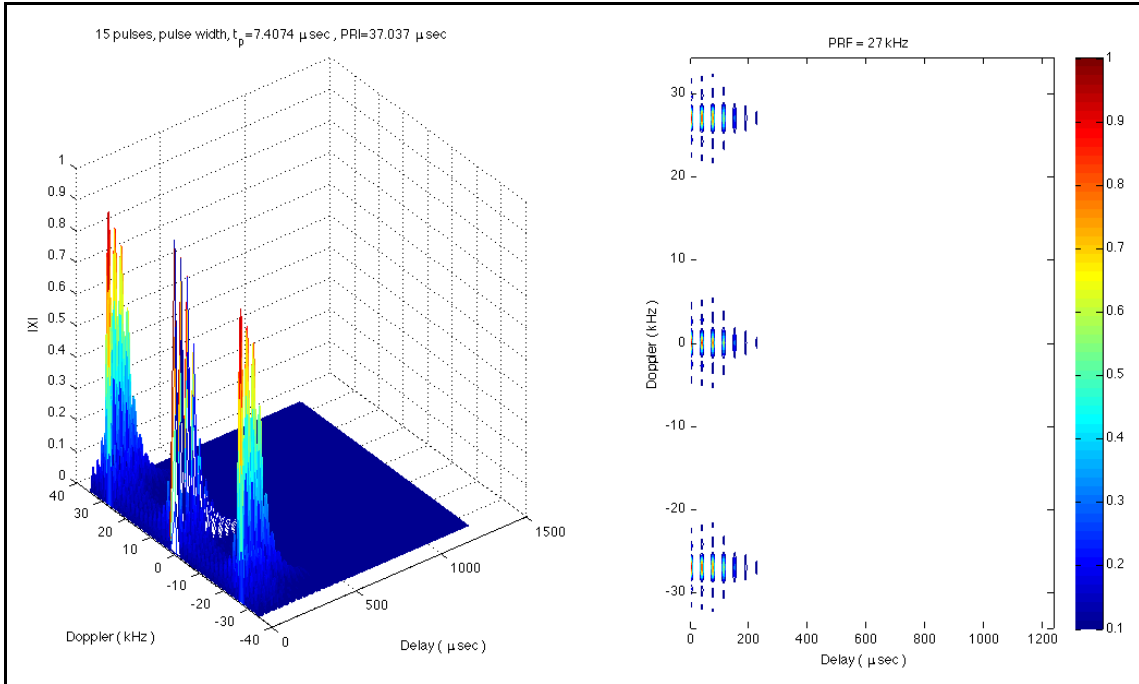


Figure 74. PRF=27 kHz , N=15 Pulses, With Clutter

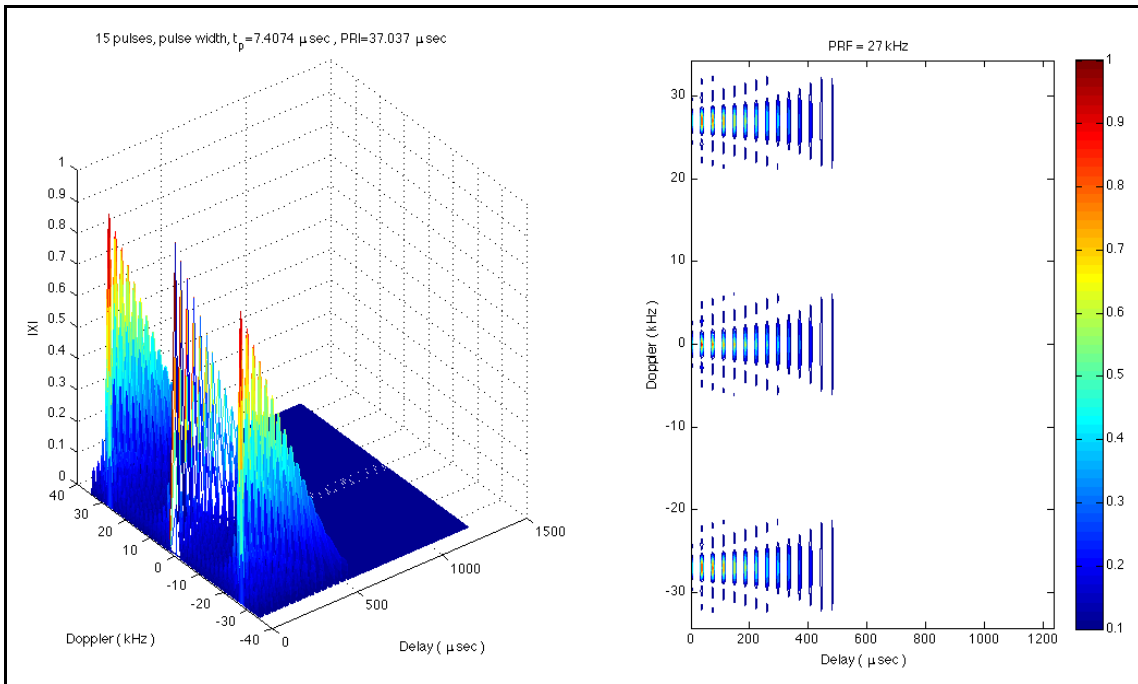


Figure 75. PRF=27 kHz , N=15 Pulses, Without Clutter

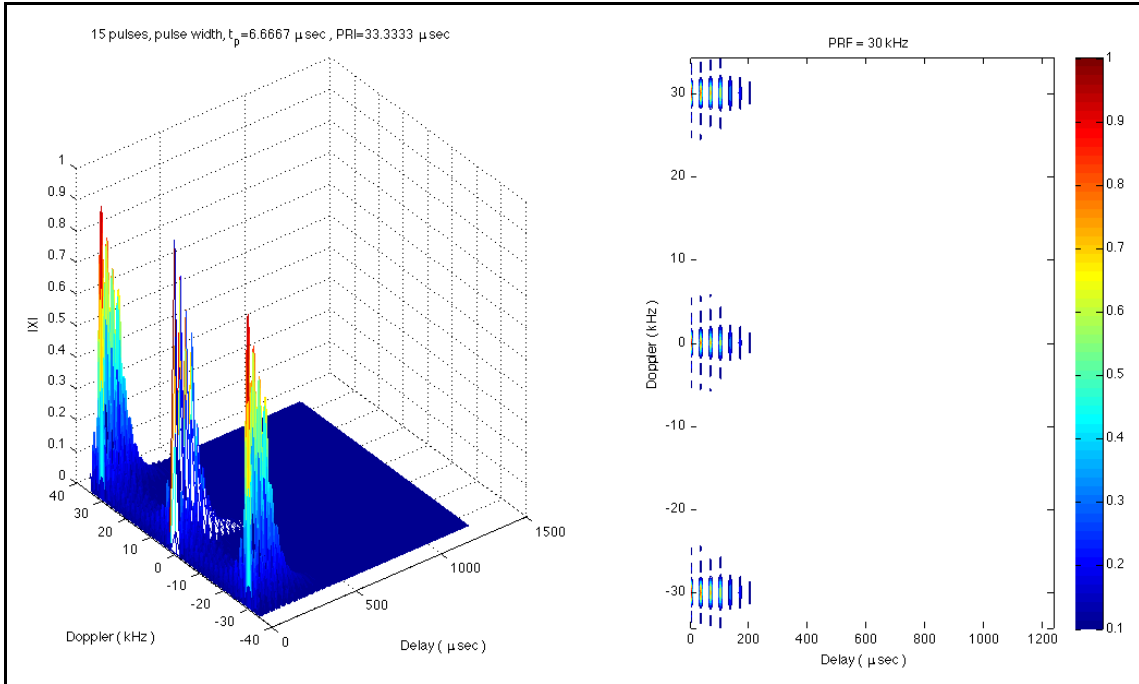


Figure 76. PRF=30 kHz , N=15 Pulses, With Clutter

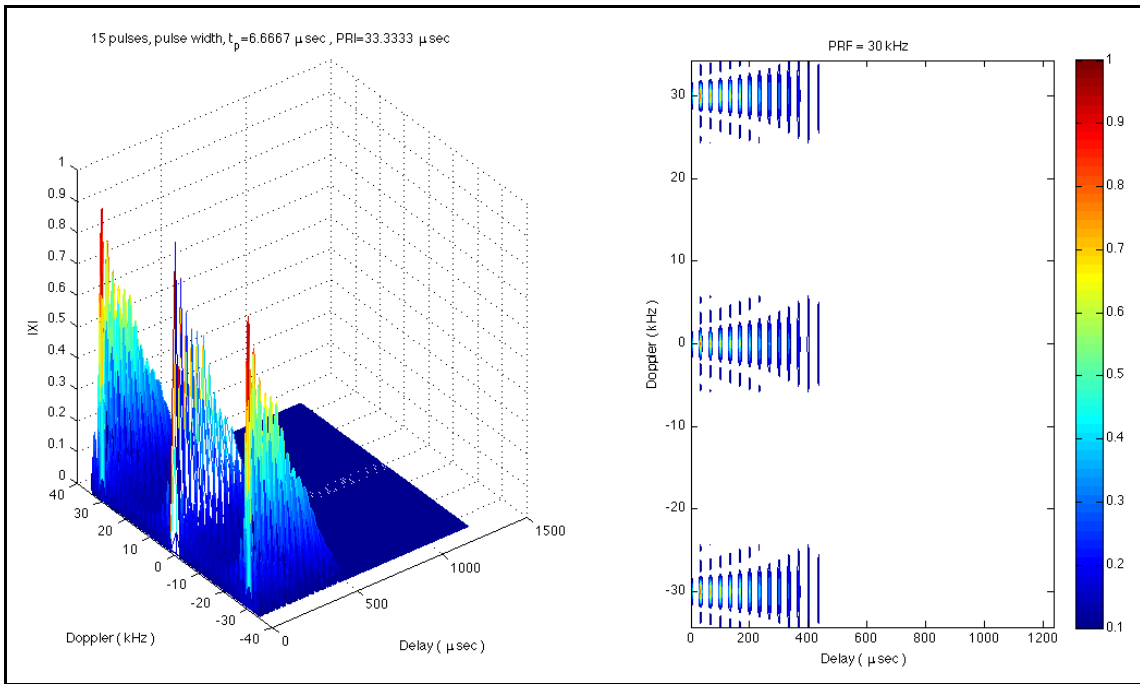


Figure 77. PRF=30 kHz , N=15 Pulses, Without Clutter

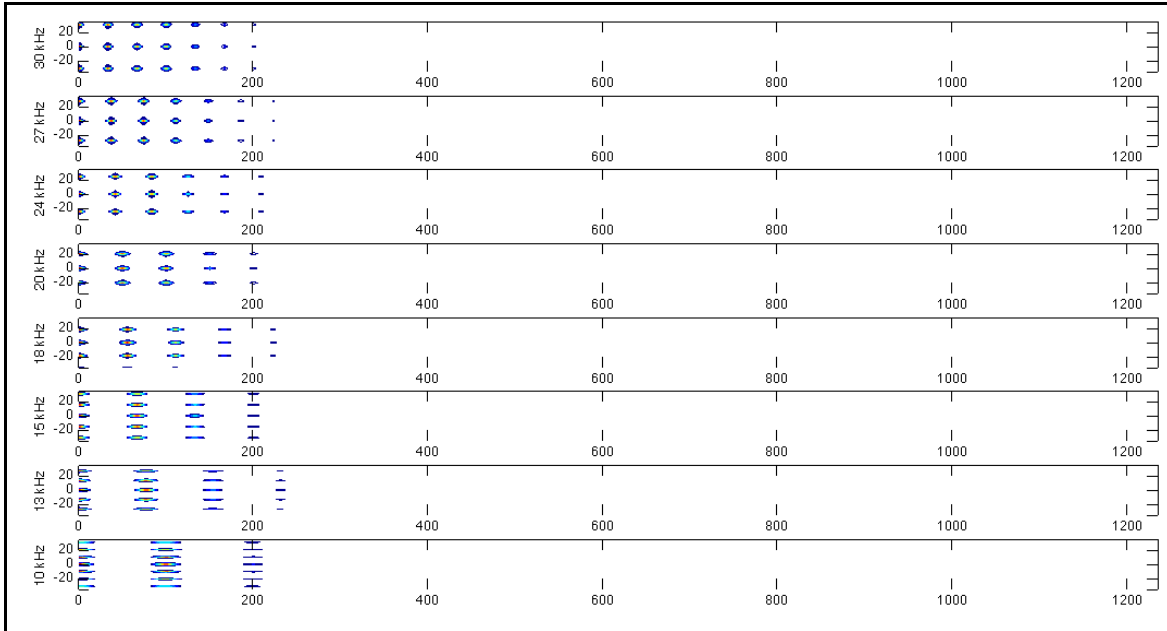


Figure 78. Comparison of PRFs With Clutter

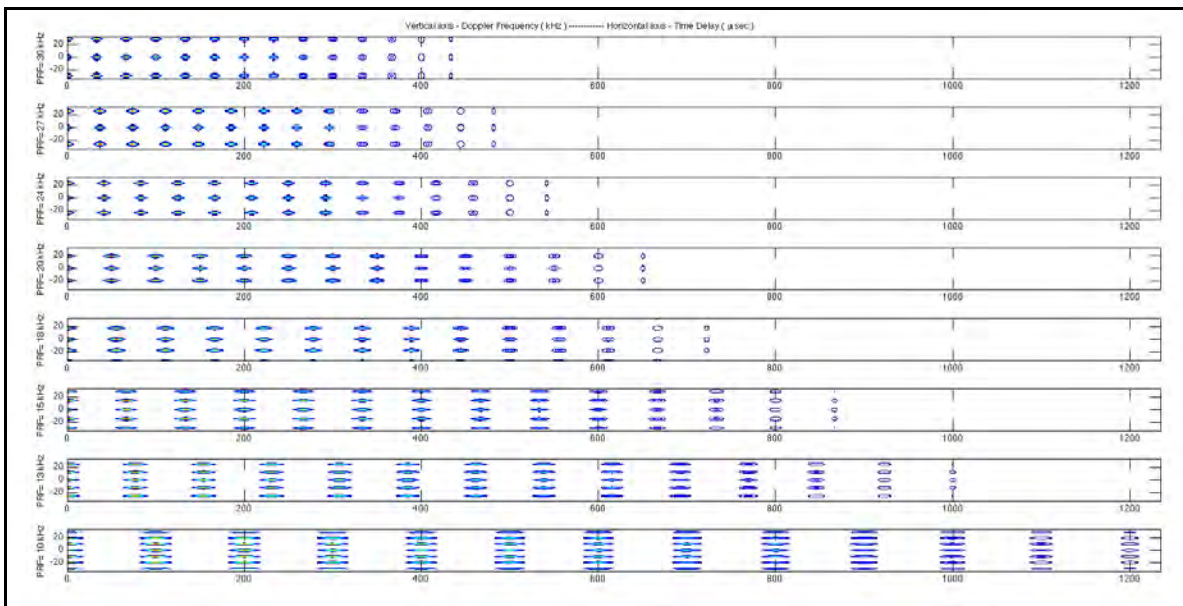


Figure 79. Comparison of PRFs Without Clutter

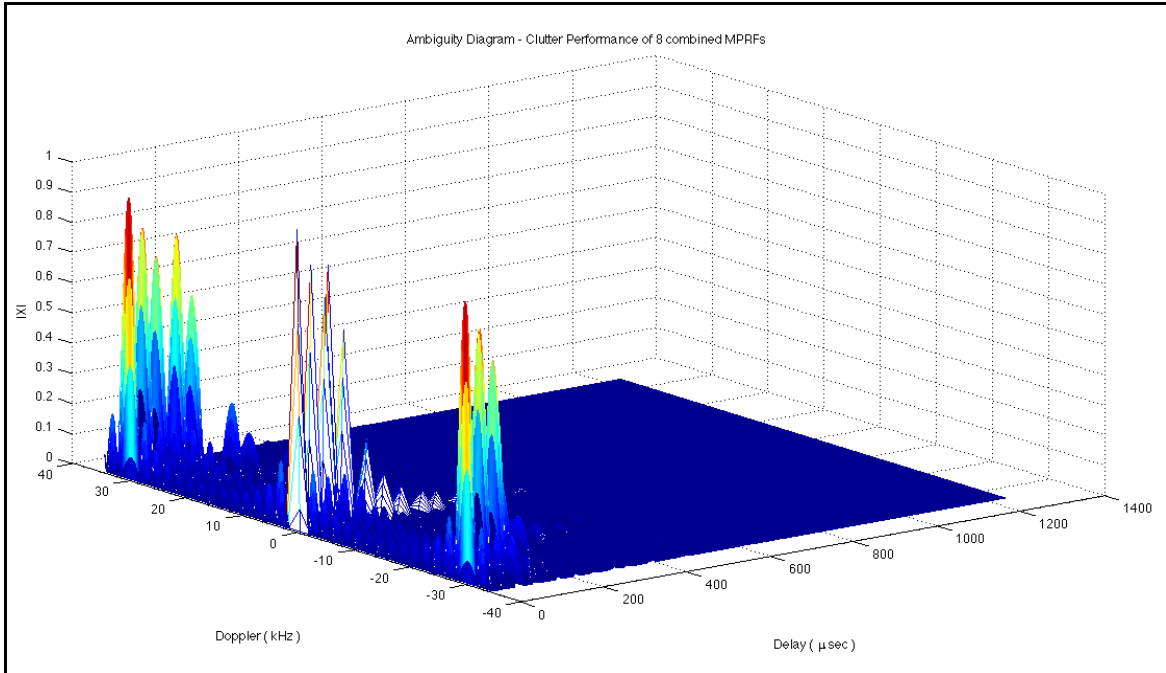


Figure 80. Ambiguity Diagram, N=15 Pulses, Combination of 8 Medium PRFs, With Clutter

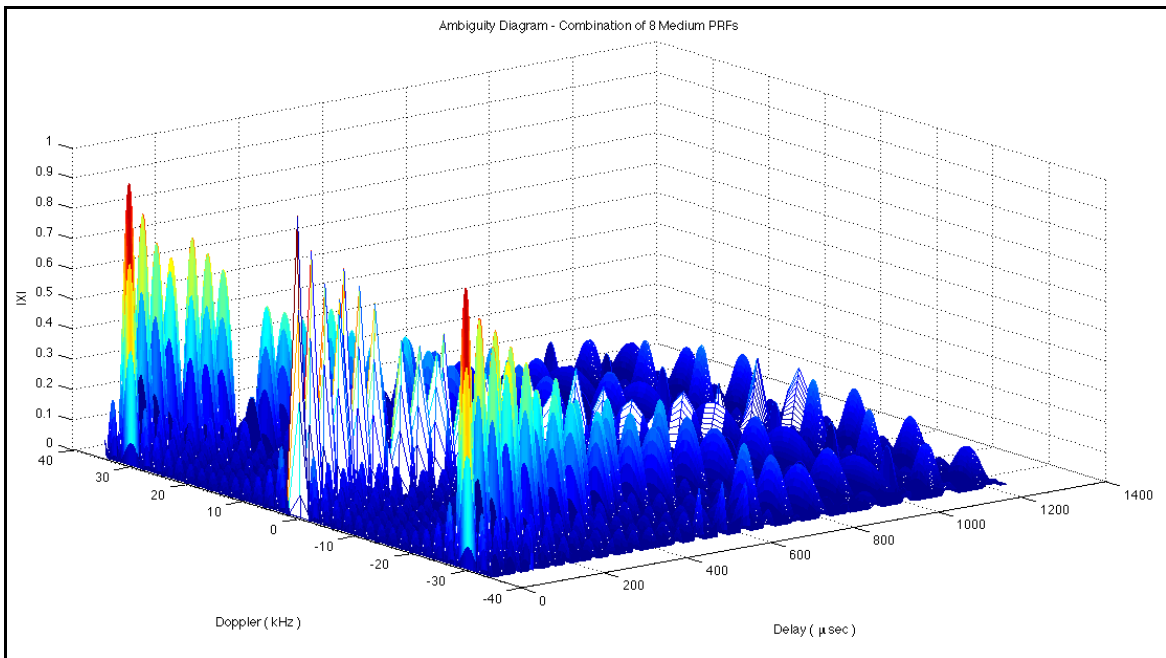


Figure 81. Ambiguity Diagram, N=15 Pulses, Combination of 8 Medium PRFs, Without Clutter

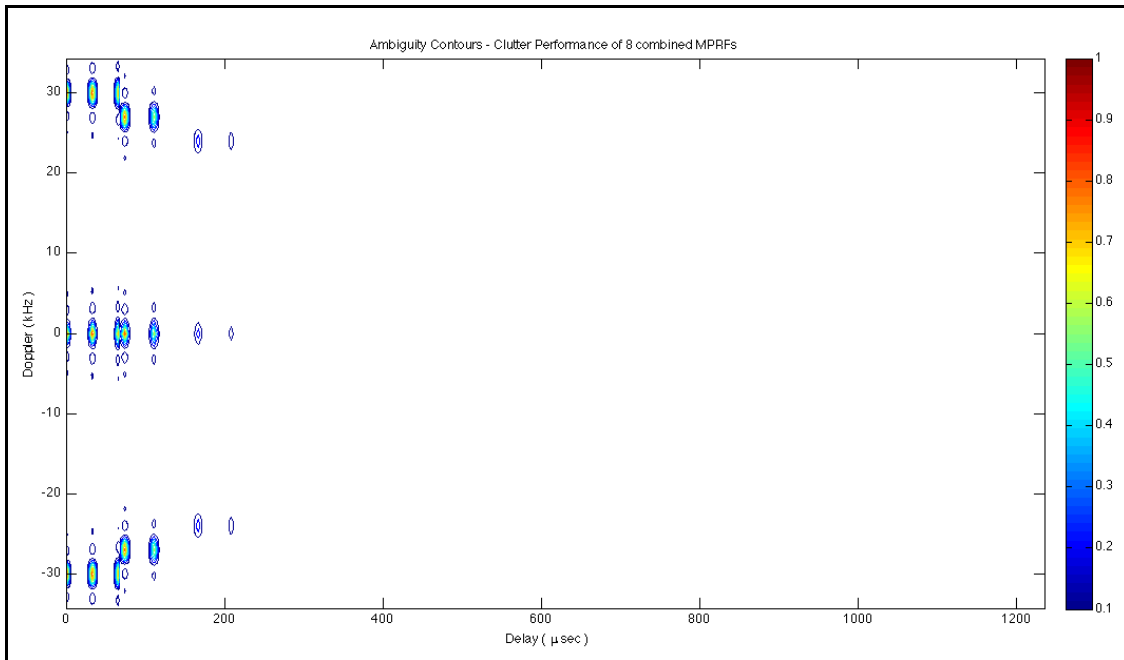


Figure 82. Ambiguity Contours, N=15 Pulses, Combination of 8 Medium PRFs, With Clutter

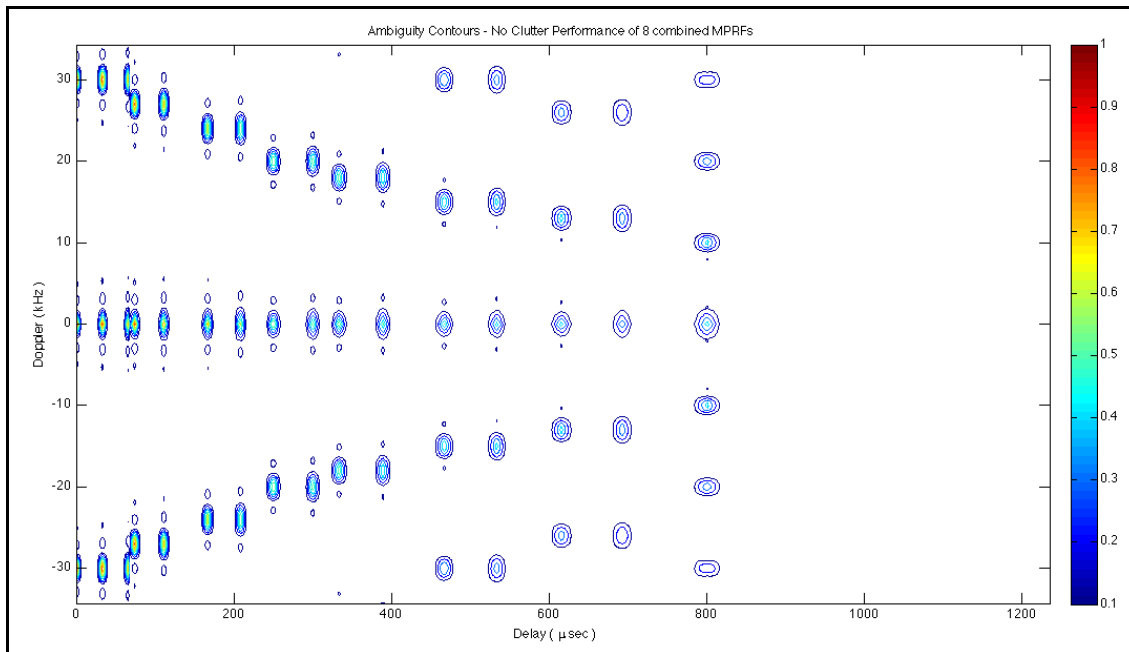


Figure 83. Ambiguity Contours, N=15 Pulses, Combination of 8 Medium PRFs, Without Clutter

4. Simulation Part II Conclusions

When we examine Figures 62 through 83, we can conclude that

- The clutter does not degrade detection for the first 100 μs of time delay. This is because of the positive value of the calculated SNR according to the given parameters (i.e., signal power well exceeds clutter power at close range where delay does not exceed 100 μs). Actually, there should have been a strong altitude return in the data but with the assumptions made for the simulation, no significant values for altitude returns are obtained from the sidelobes. After a time delay of 100 μs , the SCR decreases drastically and after approximately 200 μs of time delay, the radar loses the detection capability due to the strong clutter effect for all PRFs that are used in this simulation (Figure 84).

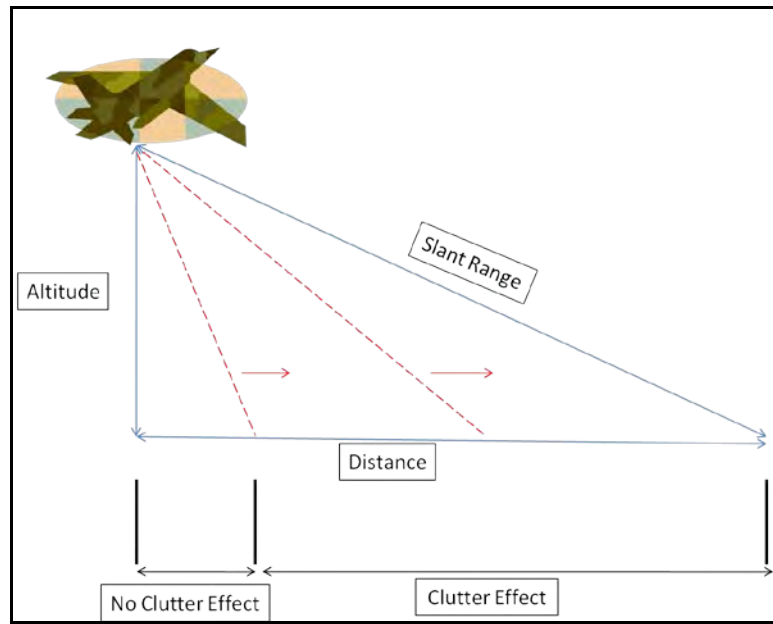


Figure 84. Clutter Effect

- Using multiple medium PRFs at approximately around 20 kHz will provide moderate ambiguities and accuracies in both time and frequency domains operating in the presence of clutter effects. However, for this part of the simulation, the best result is obtained by 13 kHz, but it is only slightly better than with 20 kHz. The improved range possible at 13 kHz can be seen in Figures 85 and 86, which follow.

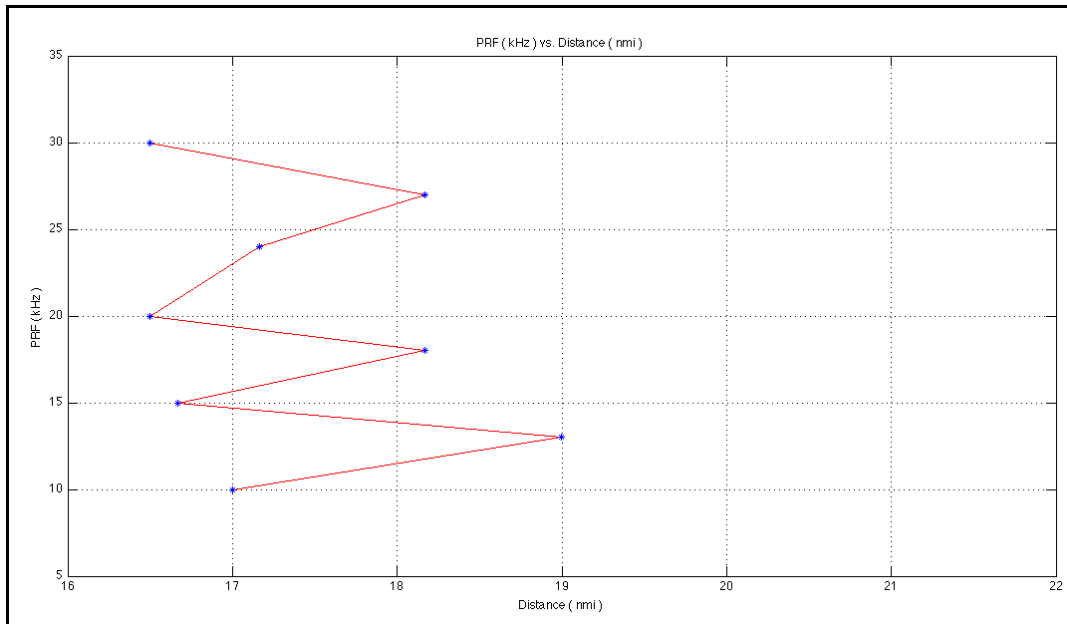


Figure 85. Simulation Results, PRF Vs. Distance

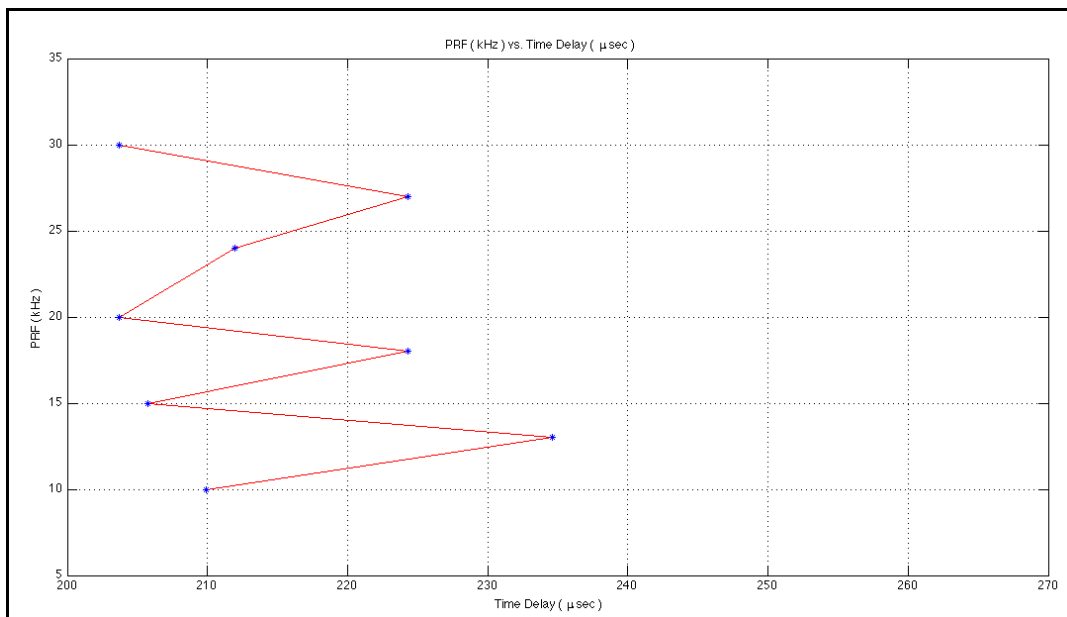


Figure 86. Simulation Results, PRF Vs. Time Delay

- In addition to the range detection limits (through delay) that are easily seen in the above diagrams, note that the clutter also affects the extent of the Doppler variation that is detectable by the radar. The clutter-free plots

when compared to those with clutter have a larger range of Doppler frequencies that are detectable than those where clutter begins to dominate the return.

- Use of multiple medium PRFs with the current sequence cannot overcome the clutter problem completely. However, different sequences may be useful. These trials will be conducted in the third part of the simulation where optimum solutions will be acquired.
- Again, the real-time environment values may be different than the simulation results as many assumptions are made and many variables are kept constant.

F. OPTIMIZATION

Optimization theory consists of mathematical methods and results that are used for finding the best solution among numerous alternatives without the necessity of evaluating all alternatives explicitly. The goals of the optimization process from an engineering perspective are creating better system models with higher efficiency and lower cost and improving the procedures for the operation of the current systems [27].

The accuracy of optimization methods to determine the best solution without evaluating all solution sets explicitly depends on the use of mathematics and iterative numerical calculations. Optimization techniques are primarily designed for computer use with regard to the needs and the complexity of the applications in engineering [27].

It is necessary to define the boundaries of a system for optimization. In addition, definition of the quantitative criterion for ranking the best solutions and selection of the variables are crucial with regard to the accuracy of the optimization process [27], [28].

As the first step of the optimization process, system boundaries are defined for approximating the real system. This procedure eliminates the system from the environment for analysis purposes. Although interaction of the system with the environment is somehow inevitable, it is assumed that no interactions take place during analysis. The boundaries may be expanded depending on the need but it must be noted that this will also increase the complexity of the system resulting in difficulties in the optimization process. Another method that can be applied is decomposition of the system. Larger systems can be broken into smaller subsystems by means of decomposition and

problems can be solved easily, but once again it must be noted that there is always a risk in dealing with the subsystems individually rather than working with a larger system as it may lead to inconsistent results [27].

In the next step, a criterion with regard to the performance or the design must be defined for evaluating the system and deciding the best set of solutions. The term “best” is generally used for either the minimum or the maximum value of the performance index in the optimization process. Several criteria can be chosen while dealing with multiple objectives. In such a case, one criterion is considered to be primary and the rest to be secondary. The primary criterion is used for the performance measure of the optimization and the secondary criteria are used for problem constraints [27].

The third step involves the selection of the independent variables that are used to characterize the system. In this selection, some variables are assumed to be fixed by external factors and some to be changeable. In addition, all of the important parameters, which affect the system, must be included in the calculation process. Last, but not least, the detail of the system must be taken into consideration while selecting the variables [27].

Once the first three steps are completed, a model must be created describing the relations between the variables themselves and the performance criterion, as well. In practical use, most of the optimization processes use simplified mathematical models of the systems, since this method is simpler and cost effective [27], [28] and does not lead to excessive complexity in the model design or performance.

G. SIMULATION PART III: LOCALIZED OPTIMIZATION

1. Simulation Part III Parameters

The parameters for the third part of the simulation are shown in Table 10. Previous studies of William H. Long, III and Keith A. Harriger [29] and Melvin B. Ringel, David H. Mooney and William H. Long, III [30] about the AN/APG-66 Radar are taken into consideration in the selection of the radar parameters to approximate the specifications of the AN/APG-68 Airborne Pulse Doppler Radar of the F-16 C/Ds, which are currently operational in the Turkish Air Force. The selected clutter parameters are the

approximate values that are likely to be seen in Turkey. In order to increase the accuracy of the localized optimization process, the number of iterations is selected as 300.

Simulation Part III Parameters	
PRFs	Randomly selected eight medium PRFs for a typical X-band radar using uniform distribution
Duty Cycle	Constant duty cycle: 20%
Minimum PRF	10 kHz
Maximum PRF	30 kHz
Operating Frequency	10 GHz
Velocity Interval	55–1,000 knots (28.3–514.4 m/s)
Doppler Shift	From -34.3 kHz to +34.3 kHz
Range Interval	0-100 nmi (0-185.2 km)
Time Delay	From -1,235 μ s to +1,235 μ s
Number of Pulses	50
PRF Switching	Pulse-to-pulse (time windows equal to PRI)
Target radar cross section	5 m ² (fighter jet)
Backscattering coefficient	-28.8 dB (average)
Altitude	2,744 m (9,000 ft)
Beamwidth	3.3 ^o
Number of Iterations	300

Table 10. Simulation Part III Parameters

2. Simulation Part III Methodology

The objective of Part III is to locally optimize the selection of medium PRFs with regard to the user queried parameters. We have incorporated the term “localized optimization” to limit the input parameters and output results to a specified set of possible values. As a reminder, in Part I the performance of the selected typical X-band radar medium PRFs are evaluated by comparing the ambiguity function values of each in a specified environment, assuming no clutter is present. In Part II, these same procedures are executed within a clutter environment. Finally, in Part III, a localized optimization process is added to Part II. In this development, different PRF sequences are compared with each other by using the ambiguity function values in order to obtain the best performance results within the specified environment. The number of different PRF sequences is defined by the user. A detailed explanation of the Part III program is presented below.

- The program displays a menu consisting of the input variables. Default values are loaded and displayed for each parameter.
- The user is queried for desired changes in any of the default parameters. The user can either run the program without making any changes, or make as many changes as required and then run the program. If the user chooses to make a change, the screen display is updated to enable the user to make the proper changes. After that the user can return to the main menu and see the updated parameters, or run the program directly.
- One of the most important parameters of the program, which enhances the reliability, is the number of iterations. The higher the iteration number is, the more reliable results the program will present. It must be noted that using over 100 iterations may take a long time for the program to compute the results. In order to obtain more accurate results, 300 iterations are set as default.
- After finishing the parameter settings, the program starts to create random PRF sequences, repeating its calculation up to the limit set by the iteration parameter. While creating these sequences, the lower limit is the minimum PRF, the upper limit is the maximum PRF, all of which are user adjustable in the parameter section as well as the number of PRFs in a sequence. The selection is executed randomly with uniform distribution. The created PRF sequences are stored in a matrix.
- Signal-to-clutter power is calculated according to the defined parameters. Positive SCR values are truncated, as they will not degrade the signal power displayed in the ambiguity function.

- The ambiguity function values are calculated for each PRF sequence. The method of how this is done is that ambiguity function values are calculated for each element of a single sequence. Then, parts of each value are combined together with regard to pulse-to-pulse switching. The number of pulses before the switching takes place is calculated according to the total number of pulses, which is also predefined by the user. Each PRF is meant to be used at least once in this calculation. For instance, assuming a PRF sequence, consisting of 8 PRFs and a total of 15 pulses, first seven of the PRFs are used with 2 pulses and the last with 1, giving a total of 15 pulses. The ambiguity function values of each PRF in a sequence are combined according to this pulse calculation. A combined ambiguity value matrix is calculated for each PRF sequence as an output. The total number of pulses is set at 50 as default.
- Later, signal-to-clutter power is added to the ambiguity values. The resulting matrix is saved in a separate matrix, which contains all the values for all PRF sequences.
- The resulting ambiguity function values for each PRF sequence are summed, presenting a maximum ambiguity value for each sequence. The higher this number is, the further distance the PRF sequence provides detection capability.
- The PRF sequence, which provides the longest detection capability, is picked among all PRF sequences, presenting a localized optimum solution based on effective performance range.
- All of the variables are stored in a file named HALDUN_LOC_OPT.mat for further review.
- In the final part of the program, the localized optimum solution for the PRF sequence and the number of iteration in which the localized optimum is reached are displayed. The user is queried to view all of the PRF sequences. The ambiguity diagram and contours are displayed afterwards.

3. Simulation Part III Plots

The plots obtained from the simulation for Part III are shown below. MATLAB codes are provided in *mprf.m* and *mprf_opt_func.m* (for Figures 87–88) in Appendix F.

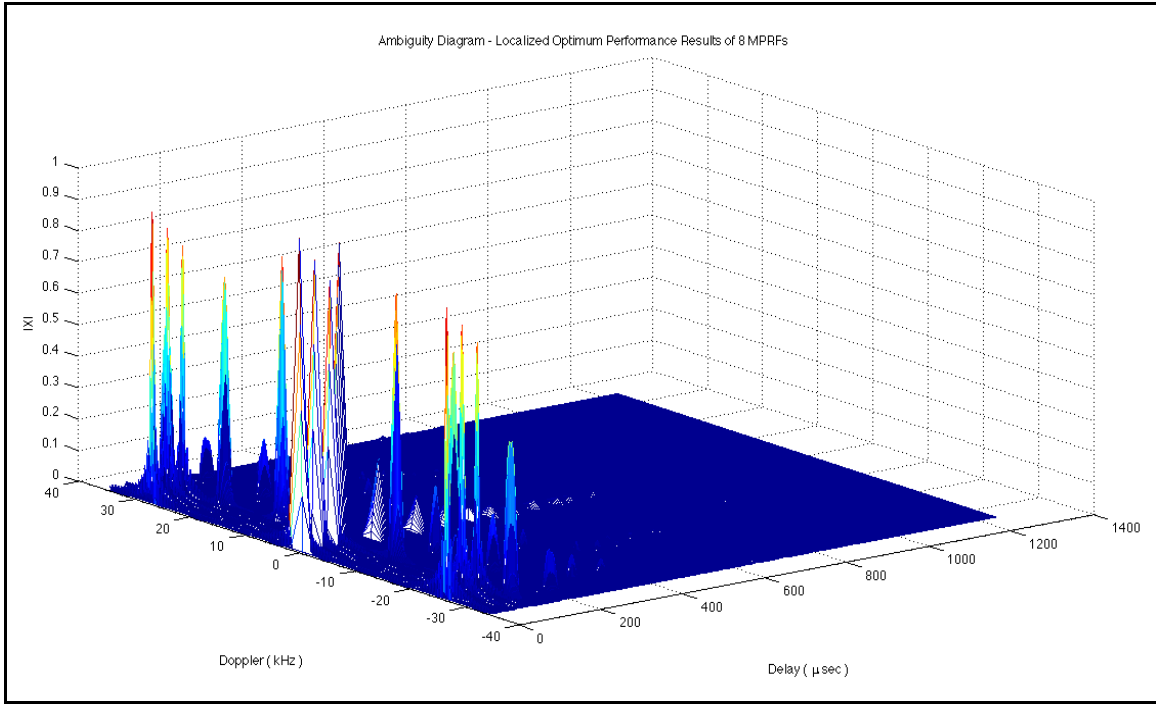


Figure 87. Ambiguity Diagram—Localized Optimum Performance of 8 MPRFs

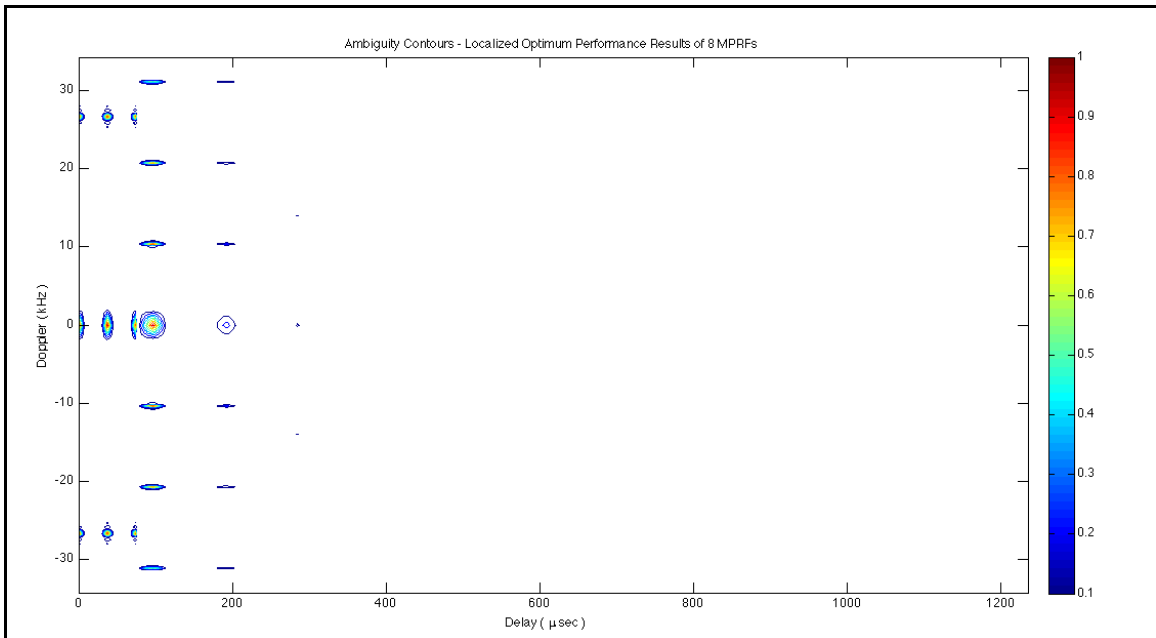


Figure 88. Ambiguity Contours—Localized Optimum Performance of 8 MPRFs

4. Simulation Part III Conclusions

In order to assure good accuracy while also keeping run times limited, the localized optimization program was run for 300 iterations for analysis. The localized optimum PRF sequence, consisting of 8 medium PRFs and chosen between 10 and 30 kHz, is 26.687, 10.377, 14.042, 19.381, 17.567, 16.807, 11.277 and 25.226 kHz, respectively. The resulting ambiguity diagram and ambiguity contours are shown in Figures 87 and 88. The complete list of the 300 PRF sequences is provided in Appendix G. Each row consists of 8 MPRFs and the localized optimum solution among these sets of PRFs is highlighted in yellow. Interpretations of the localized optimization results follow:

- The localized optimum PRF sequence provides a detection range of 23.17 nmi (42.9 km), which corresponds to a time delay of 286.0311 μ s under the model's specified parameters. The parameters that were used in this simulation are shown below as they are displayed in the main menu of the program.

```
*****
*****
*****          PARAMETERS          *****
*****
*****
1. Minimum PRF Value (kHz) -----> 10
2. Maximum PRF Value (kHz) -----> 30
3. Number of PRFs -----> 8
4. Operating Frequency (GHz) -----> 10
5. Constant Duty Cycle -----> 0.2
6. Minimum Velocity (knots) -----> 55
7. Maximum Velocity (knots) -----> 1000
8. Maximum Distance (nmi) -----> 100
9. Number of Pulses -----> 50
10. Target RCS (m^2) -----> 5
11. Backscatter Coefficient (dB) ----> -28.8
12. Altitude (ft) -----> 9000
13. HPBW (degrees) -----> 3.3
14. Number of Iterations -----> 300
15. No change. Run the program

What would you like to change?

Please enter a number (1-15) ----->
```

Figure 89. Parameters of Simulation-Part III

- It must be noted that the simulation provides only a localized optimum solution within the given parameters. Thus, different solutions than the stated results may exist, and they may even be better than those shown. Figures 90 and 91 show the results for another run of the simulation with

the same parameters, but this time the selected localized optimum PRF sequence is 28.537, 10.165, 26.492, 25.346, 29.942, 14.553, 28.39 and 22.839 kHz. There is only a slight difference between the detection performances of both results. The ambiguity contours of the two trials show similarities (Figures 88 and 91).

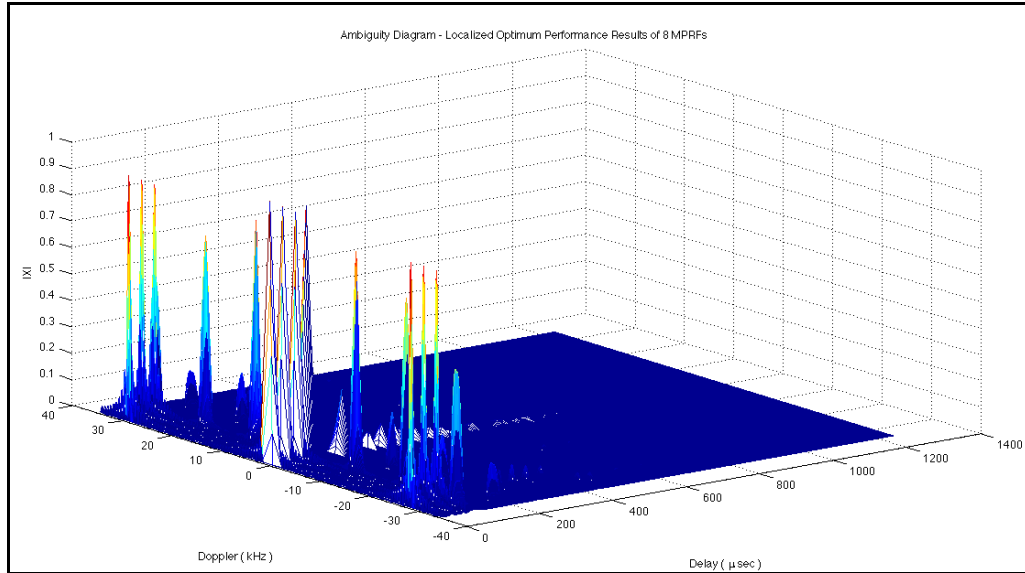


Figure 90. Ambiguity Diagram—Second Run of the Program

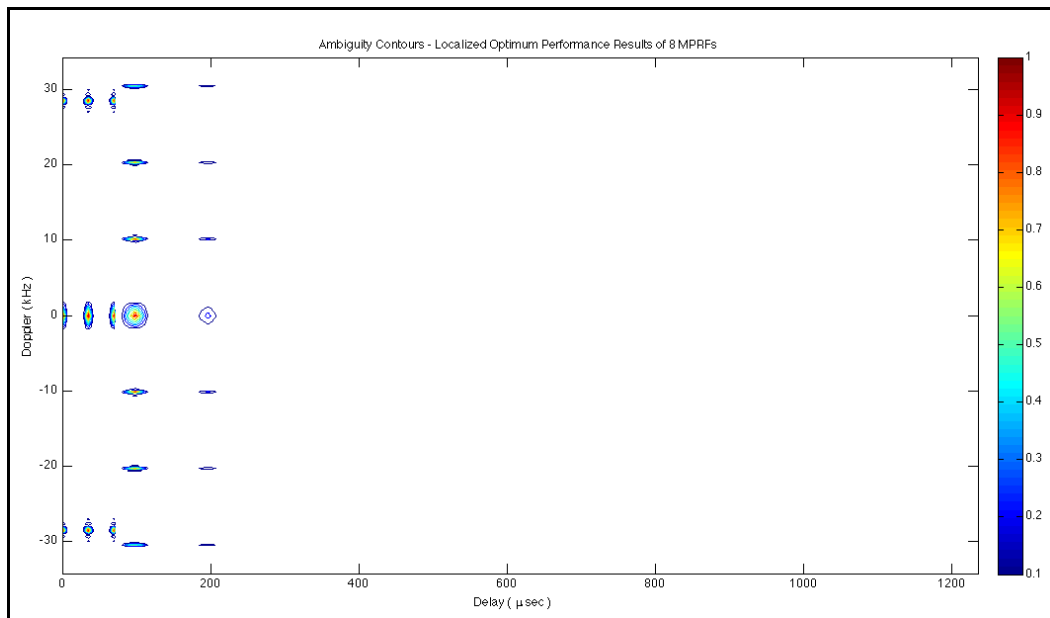


Figure 91. Ambiguity Contours—Second Run of the Program

- As expected, the clutter continues to adversely affect the extent of the Doppler variation that is detectable by the radar.
- Although many different multiple MPRF sequences were tried in this part of the simulation, none of them succeeded in overcoming the clutter problem completely.
- Once again, the real-time environment values may be different than the simulation results as many assumptions are made and many variables are kept constant.
- Instead of using 15 pulses, a total number of 50 pulses were used in this part of the simulation. This change resulted in better Doppler accuracy and worse range accuracy as seen in Figure 88.
- The clutter does not degrade detection for the first 100 μs of time delay. This is because of the positive value of the calculated SNR according to the given parameters (i.e., signal power well exceeds clutter power at close range). Actually, there should have been a strong altitude return in the data but with the assumptions made for the simulation, no significant values for altitude returns are obtained from the sidelobes. After a time delay of 100 μs , the SCR decreases drastically and after approximately 290 μs of time delay, the radar loses the detection capability due to the strong clutter effect for all PRFs that are used in this simulation (Figure 88).
- Using multiple medium PRFs at approximately around 20 kHz will provide moderate ambiguities and accuracies in both time and frequency domains under clutter effects. However, for this part of the simulation, there are multiple localized optimum solutions within the given parameters.

V. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

There are many modern radar systems that use medium PRF waveforms in order to increase the accuracy and decrease the ambiguity in the measurement of the target range and velocity in an environment where clutter is present [31]. The clutter is widely spread in velocity and range cells due to the low grazing angles and the returns in the sidelobes of the antenna [32]. The clutter rejection characteristics of medium PRF radars have significance in many systems, such as airborne intercept and fire control [31]. Medium PRF waveforms provide the best performance in all aspect conditions and in the presence of strong clutter [32].

The advantage of medium PRF compared to low PRF is that it provides better mainbeam clutter rejection by Doppler filtering and results in fewer targets that are rejected. On the other hand, medium PRF is advantageous over high PRF as medium PRF has better performance against sidelobe clutter in a tail-chase aspect. Targets can be extracted from the sidelobe clutter with the help of Doppler filtering and range gating in combination [33].

A radar may suffer from ambiguous range and Doppler data if a single medium PRF is used. This may result in several blind regions both in range and velocity. This problem can be solved by using multiple medium PRFs. In basic terms, the requirement is M target detections out of N medium PRFs. It is known as M of N scheme and the commonly used scheme is 3 of 8. The objective is to find the appropriate combinations of medium PRFs in order to diminish the blind zones, resolve the ambiguities both in range and Doppler, avoid ghosting and decrease the possibility of false targets [31].

This thesis provides a brief discussion on the fundamentals of Doppler radar and PRF categories, with emphasis on medium PRF, especially with regard to X-band radars. A simulation model is developed in order to observe the performance of medium PRF in airborne pulse Doppler radars in a theater involving low altitude, air-to-air moderate range radar capability and an acceptable range and Doppler resolution within that

environment. The simulation consists of three parts: clutter-free, clutter, and multiple PRFs in the presence of clutter. Previous studies [15], [34] and the MATLAB codes compiled by Dr. David Jenn [35], contributed greatly to the first part of the simulation, where the performance of multiple medium PRFs is examined in a nonclutter environment. In the second part of the simulation, ground clutter is added. Numerous previous studies about ground clutter modeling [8], [36], [37], [38], [39], [40] have been examined and a simpler model was developed meeting the criteria that are present in Turkey. According to the results of both parts, the use of multiple medium PRFs with values approximately around 20 kHz gives good detection performance under given circumstances. The effect of ground clutter is observed as the detection range is degraded when clutter is applied.

In the final part of the simulation, a localized optimum PRF set was reached with regard to detection performance. Once again, a simpler model was developed compared to the previous studies of C.A. Alabaster and E.J. Hughes [31], [33]. The objective of the third part is to find a localized optimum selection of specified amount of typical X-band radar medium PRFs within given parameters. The parameters used in this part of the simulation were approximated to the values of the AN/APG-68 airborne radar and the clutter characteristics of Turkey.

The simulation enables the user to analyze the performance of medium PRFs under desired conditions. It must be noted that the values obtained from the simulation may differ from the real environment values, since many assumptions were made and certain values were kept constant in order to simplify the optimization process.

Consequently, the advantages and limitations of medium PRF in airborne pulse Doppler radars are presented. From the Turkish Air Force perspective, since the developed model examines specific conditions, the model can be upgraded to an advanced level according to the needs and capabilities of the Turkish Air Force and can be an example model for improved future studies.

B. RECOMMENDATIONS

It is obvious that medium PRF has certain advantages in specified areas. The research conducted under this thesis tried to examine these features and created a model in order to simulate the environment and the equipment of the author's country, Turkey. The simulation model can be a starting point and be improved in several ways for future studies. Instead of making assumptions, using fixed values and omitting certain facts in order to reduce the complexity, detailed studies can be carried out. In the selection of PRFs, Chinese remainder theorem can be implemented for better decodability margins. In addition, mapping of ground clutter can be improved in order to obtain better results. Different PRF schedules can be examined for better performance results. The academic studies that have been used as references in this thesis are the primary resources that can lead to future research and improvements in medium PRF radars.

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APPENDIX A

Band Designation	Nominal Frequency Range	Specific Frequency Ranges for Radar Based on ITU Assignments for Region 2
HF	3–30 MHz	
VHF	30–300 MHz	138–144 MHz 216–225 MHz
UHF	300–1000 MHz	420–450 MHz 850–942 MHz
L	1–2 GHz	1215–1400 MHz
S	2–4 GHz	2300–2500 MHz 2700–3700 MHz
C	4–8 GHz	5250–5925 MHz
X	8–12 GHz	8500–10680 MHz
K _u	12–18 GHz	13.4–14.0 GHz 15.7–17.7 GHz
K	18–27 GHz	24.05–24.25 GHz
K _a	27–40 GHz	33.4–36.0 GHz
V	40–75 GHz	59–64 GHz
W	75–110 GHz	76–81 GHz 92–100 GHz
mm	110–300 GHz	126–142 GHz 144–149 GHz 231–235 GHz 238–248 GHz

Table 11. IEEE Standard Radar-Frequency Letter Band Nomenclature (From [10])

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APPENDIX B

```
% ambiguity_comparison.m
```

```
clear all
close all
clc
%% Input
f=10e9; %Operating frequency
c=3e8; %Speed of light
lambda=c/f; %Wavelength
dutycycle=0.2; %Constant duty cycle
PRF=[30e3 10e3]; %Pulse repetition frequencies
PRIlist=1./PRF; %Pulse repetition intervals

%% Doppler frequency
vr=linspace(55*0.51444445,1000*0.51444445,300); %Radial
velocity interval 55-1000 knots
doppler=2.*vr/lambda;
for g=1:300
    a(1,g)=doppler(1,(301-g));
end
fd=[-a 0 doppler]; %Doppler frequencies

%% Time delay
delaymax=2*185200/c;
delay=linspace(-delaymax,delaymax,601); %time delay
%%
N=15; %Number of pulses
p=[-(N-1):(N-1)];

%% Ambiguity Function of a Pulse Train

for h=1:length(PRIlist)
    PRI=PRIlist(h);
    pulsewidth(h)=PRI.*0.2;
for i=1:length(fd)
    for k=1:length(delay)
        sum=0;

        for n=1:length(p)
            A=1-abs(delay(k)-p(n)*PRI)/pulsewidth(h);
```

```

        Xc=A;

        if abs(pi*pulsewidth(h)*A*fd(i))>1e-4
Xc=abs(A*sin(pi*pulsewidth(h)*A*fd(i))/(pi*pulsewidth(h)*A*
fd(i)));
        end

        B=0;
        if abs(delay(k)-p(n)*PRI)<=pulsewidth(h)
        B=N-abs(p(n));

        if abs(sin(pi*fd(i)*PRI))>1e-5
            B=sin(pi*fd(i)*(N-
abs(p(n))*PRI)/sin(pi*fd(i)*PRI);
        end

        end
        sum=sum+abs(B)*Xc;

        end
        X(i,k)=sum/N;

    end

end
figure(h)

%% Plot
subplot(1,2,1)
mesh(delay.*1e6,fd./1e3,X)
xlabel('Delay ( \musec )'),ylabel('Doppler ( kHz )'),
zlabel('|X|')
title([num2str(N),' pulses, pulse width,
t_p=',num2str(pulsewidth(h).*1e6),' \musec ,
PRI=',num2str(PRI.*1e6) '\musec `'])
subplot(1,2,2)
contour(delay.*1e6,fd./1e3,X)
xlabel('Delay ( \musec )'),ylabel('Doppler ( kHz )')
title(['PRF = ',num2str(PRF(h)/1e3),' kHz `'])

figure(length(PRF)+1)
subplot(length(PRF),1,h)
contour(delay.*1e6,fd./1e3,X)
ylabel([num2str(PRF(h)/1e3),' kHz'])
end

```


APPENDIX C

```
%*****%
%
% no_clut.m %
%
% Use: To calculate ambiguity function for each of %
% the of the selected PRFs in an environment, %
% assuming no clutter is present and to create %
% a combined PRF sequence with regard to user %
% queried parameters using function %
% "no_clut_func" %
%
% Inputs: -PRF Values (Hz) %
% -Number of PRFs %
% -Operating Frequency (Hz) %
% -Constant Duty Cycle %
% -Minimum Velocity (knots) %
% -Maximum Velocity (knots) %
% -Maximum Distance (nmi) %
% -Number of Pulses %
%
% Output: -Ambiguity values of each PRF and %
% the combined sequence. %
% -Ambiguity diagram and contour %
% plots of the outputs %
% -An ambiguity contour comparison %
% plot that contains all of the %
% individual plots of each PRF %
%
%
%*****%

clear all
close all
clc

%% Default Parameters

useprf=8; % Number of PRFs that will be used
f=10e9; % Operating frequency (Hz)
```

```

dc=0.2;           % Constant Duty cycle
vrmin=55;        % Minimum radial velocity (knots)
vrmax=1000;     % Maximum radial velocity (knots)
dmax=100;       % Maximum distance (nmi)
N=15;          % Number of pulses
PRF=[30e3 27e3 24e3 20e3 18e3 15e3 13e3 10e3]; %PRF
sequence
%% Main menu
newvar=1;
while newvar==1
    clc

display('*****
*****');
    display('*****
*****');
    display('*****                PARAMETERS
*****');
    display('*****
*****');

display('*****
*****');
    display(' ');
    display(['1. PRF Sequence (kHz) ----->
',num2str(PRF./1e3)]); %default values
    display(['2. Number of PRFs ----->
',num2str(useprf)]);
    display(['3. Operating Frequency (GHz) ----->
',num2str(f/1e9)]);
    display(['4. Constant Duty Cycle ----->
',num2str(dc)]);
    display(['5. Minimum Velocity (knots) ----->
',num2str(vrmin)]);
    display(['6. Maximum Velocity (knots) ----->
',num2str(vrmax)]);
    display(['7. Maximum Distance (nmi) ----->
',num2str(dmax)]);
    display(['8. Number of Pulses ----->
',num2str(N)]);
    display('9. No change. Run the program');
    display(' ');
    display('What would you like to change?');
    display(' ');

```

```

ch_par=input('Please enter a number (1-9) -----> ');
display(' ');

%% Set New Parameters - Menu Options

switch ch_par

    case 1 %Set new PRFs
        clc
        clear PRF
        for j=1:useprf
            PRF(1,j)=input(['Enter PRF #',num2str(j),' in
Hz (i.e. 10e3) -----> ']);
            while PRF(1,j)<=0 %Error check
                display(' ');
                display('%%%%%%%%%% Please enter a
positive PRF value %%%%%%%%%%');
                display(' ');
                PRF(1,j)=input(['Enter PRF #',num2str(j),'
in Hz (i.e. 10e3) -----> ']);
            end
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
');
        while menu_opt~=1 & menu_opt~=2 %Error check
            display(' ');
            menu_opt=input('Please choose 1 or 2 -----
--> ');
        end
        if menu_opt==2
            newvar=2;
        end
    end
end

```

```

    case 2 %Set new number of PRFs
        clc
        useprf=input('Enter the number of medium PRFs (i.e.
8) -----> ');
        while useprf<=0 | useprf>N %Error check
            display(' ');
            display(['%%%% Please enter a positive
value smaller than the number of pulses (',num2str(N),'
%%%%']);
            display(' ');
            useprf=input('Enter the number of medium PRFs
(i.e. 8) -----> ');
        end

        clc
        clear PRF
        for j=1:useprf
            PRF(1,j)=input(['Enter PRF #',num2str(j),' in
Hz (i.e. 10e3) -----> ']);
            while PRF(1,j)<=0 %Error check
                display(' ');
                display('%%%%%%%% Please enter a
positive PRF value %%%%%%%%%');
                display(' ');
                PRF(1,j)=input(['Enter PRF #',num2str(j),'
in Hz (i.e. 10e3) -----> ']);
            end
        end
    end

    display(' ');
    display('What would you like to do next?');
    display(' ');
    display('1. Return to main menu');
    display('2. Run the program');
    display(' ');
    menu_opt=input('Please choose 1 or 2 ----->
');
    while menu_opt~=1 & menu_opt~=2 %Error check
        display(' ');
        menu_opt=input('Please choose 1 or 2 -----
--> ');
    end
    if menu_opt==2

```

```

        newvar=2;
    end

    case 3 %Set new operating frequency
        clc
        f=input('Enter Operating Frequency in Hz (i.e.
10e9) -----> ');
        while f<=0
            display(' ');
            display('%%%%%%%%%% Please enter a positive
number %%%%%%%%%');
            display(' ');
            f=input('Enter Operating Frequency in Hz (i.e.
10e9) -----> ');
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
');
        while menu_opt~=1 & menu_opt~=2 %Error check
            display(' ');
            menu_opt=input('Please choose 1 or 2 -----
--> ');
        end
        if menu_opt==2
            newvar=2;
        end

    case 4 %Set new constant duty cycle
        clc
        dc=input('Enter Constant Duty Cycle Between 0 and 1
(i.e. 0.2) ----> ');
        while dc<0 | dc>1 % Error check
            display(' ');
            display('%%%%%%%%%% Please enter a number
between 0 and 1 %%%%%%%%%');
            display(' ');
            dc=input('Enter Constant Duty Cycle Between 0

```

```

and 1 (i.e. 0.2) ----> ');
    end
    display(' ');
    display('What would you like to do next?');
    display(' ');
    display('1. Return to main menu');
    display('2. Run the program');
    display(' ');
    menu_opt=input('Please choose 1 or 2 ----->
');
    while menu_opt~=1 & menu_opt~=2 %Error check
        display(' ');
        menu_opt=input('Please choose 1 or 2 -----
--> ');
    end
    if menu_opt==2
        newvar=2;
    end

    case 5 %Set new minimum velocity (knots)
        clc
        vrmin=input('Enter Min. Radial Velocity in knots
(i.e. 55) -----> ');
        while vrmin<0 | vrmin>=vrmax %Error check
            display(' ');
            display(['%%%%%%%%% Please enter a positive
number smaller than max. radial velocity
(',num2str(vrmax),') %%%%%%%%%%']);
            display(' ');
            vrmin=input('Enter Min. Radial Velocity in
knots (i.e. 55) -----> ');
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
');
        while menu_opt~=1 & menu_opt~=2 %Error check
            display(' ');
            menu_opt=input('Please choose 1 or 2 -----

```

```

--> `);
    end
    if menu_opt==2
        newvar=2;
    end

    case 6 %Set new maximum velocity (knots)
        clc
        vrmax=input('Enter Max. Radial Velocity in knots
(i.e. 1000) -----> `);
        while vrmax<0 | vrmax<=vrmin %Error check
            display(' ');
            display(['%%%%%%%% Please enter a positive
number greater than min. radial velocity
(',num2str(vrmin),') %%%%%%%%%']);
            display(' ');
            vrmax=input('Enter Max. Radial Velocity in
knots (i.e. 1000) -----> `);
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
`);
        while menu_opt~=1 & menu_opt~=2 %Error check
            display(' ');
            menu_opt=input('Please choose 1 or 2 -----
--> `);
        end
        if menu_opt==2
            newvar=2;
        end

    case 7 % Set new maximum distance
        clc
        dmax=input('Enter Max. Distance in nmi (i.e. 100) -
-----> `);
        while dmax<=0 %Error check
            display(' ');

```

```

        display('%%%%%%%%%% Please enter a
positive number %%%%%%%%%');
        display(' ');
        dmax=input('Enter Max. Distance in nmi (i.e.
100) -----> ');
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
');
        while menu_opt~=1 & menu_opt~=2 %Error check
            display(' ');
            menu_opt=input('Please choose 1 or 2 -----
--> ');
        end
        if menu_opt==2
            newvar=2;
        end

        case 8 % Set new number of pulses
            clc
            N=input('Enter Number of Pulses (i.e. 15) -----
-----> ');
            while N<0 | N<useprf %Error check
                display(' ');
                display(['%%%%%%%%% Please enter a positive
number greater than the number of PRFs
(',num2str(useprf),') %%%%%%%%%']);
                display(' ');
                N=input('Enter Number of Pulses (i.e. 15) -----
-----> ');
            end
            display(' ');
            display('What would you like to do next?');
            display(' ');
            display('1. Return to main menu');
            display('2. Run the program');
            display(' ');
            menu_opt=input('Please choose 1 or 2 ----->

```



```

');
    while menu_opt~=1 & menu_opt~=2 %Error check
        display(' ');
        menu_opt=input('Please choose 1 or 2 -----
--> ');
    end
    if menu_opt==2
        newvar=2;
    end

    case 9 %Run the program
        newvar=2;

    otherwise
        clc
        newvar=1;

end
end
%%
clc
display(' ');
display('%%%%%%%%%%');
display('%%%%%%%%%%');
display('%%%%%%%%%% PLEASE WAIT');
display('%%%%%%%%%%');
display('%%%%%%%%%% COMPUTING ...');
display('%%%%%%%%%%');
display('%%%%%%%%%%');
display(' ');
%%

X_TOT=no_clut_func(PRF,useprf,f,dc,vrmin,vrmax,dmax,N);

```

```
%%
```

```
load HALDUN_NO_CLUT.mat
```

```
clc
```

```
*****%  
% %  
% no_clut_func.m %  
% %  
% Use: To calculate ambiguity function for each %  
% of the selected PRFs in an environment, %  
% assuming no clutter is present and to %  
% create a combined PRF sequence with %  
% regard to user queried parameters %  
% %  
% Inputs: -PRF Values (Hz) %  
% -Number of PRFs %  
% -Operating Frequency (Hz) %  
% -Constant Duty Cycle %  
% -Minimum Velocity (knots) %  
% -Maximum Velocity (knots) %  
% -Maximum Distance (nmi) %  
% -Number of Pulses %  
% %  
% Output: -Ambiguity values of each PRF %  
% and the combined sequence. %  
% -Ambiguity diagram and contour %  
% plots of the outputs %
```

```

%           -An ambiguity contour comparison %
%           plot that contains all of the   %
%           individual plots of each PRF     %
%                                           %
%*****%

function
X_TOT=no_clut_func(PRF,useprf,f,dc,vrmin,vrmax,dmax,N)

%% Computation

c=3e8;    % speed of light
lambda=c/f;    % wavelength
p=[-(N-1):(N-1)];

%% Doppler Frequency

vr=linspace(vrmin*0.51444445,vrmax*0.51444445,300); %Radial
velocity interval
doppler=2.*vr/lambda;
for haldun1=1:300
    dop_fr(1,haldun1)=doppler(1,(301-haldun1));
end
fd=[-dop_fr 0 doppler]; %Doppler frequencies

%% Time delay
dmin=0;
delaymin=0;
delaymax=2*1852*dmax/c;
delay=linspace(delaymin,delaymax,601); %time delay

%% Pulse to pulse switching

p_sw=ones(1,useprf);
tot_p_sw=sum(p_sw);

    for haldun2=1:useprf
        if tot_p_sw~=N
            p_sw(haldun2)=p_sw(haldun2)+1;
        end
        tot_p_sw=sum(p_sw);
    end

```

```

end

%% Ambiguity Function of a Pulse Train
PRI_list=1./PRF;

X_TOT=zeros(601,601);

alpha=0;
beta=1;
cum_delay=zeros(1,length(PRI_list)+1);
X_final=zeros(601,601);

for haldun3=1:length(PRI_list)
    PRI=PRI_list(haldun3);
    pulsewidth(haldun3)=PRI.*dc;
for i=1:length(fd)
    for k=1:length(delay)
        sumtot=0;

        for n=1:length(p)
            A=1-abs(delay(k)-p(n)*PRI)/pulsewidth(haldun3);
            Xc=A;

            if abs(pi*pulsewidth(haldun3)*A*fd(i))>1e-4

Xc=abs(A*sin(pi*pulsewidth(haldun3)*A*fd(i))/(pi*pulsewidth
(haldun3)*A*fd(i)));
                end

                B=0;
                if abs(delay(k)-p(n)*PRI)<=pulsewidth(haldun3)
                    B=N-abs(p(n));

                    if abs(sin(pi*fd(i)*PRI))>1e-5
                        B=sin(pi*fd(i)*(N-
abs(p(n)))*PRI)/sin(pi*fd(i)*PRI);
                    end

                end

                sumtot=sumtot+abs(B)*Xc;

            end

        end
        X(i,k)=sumtot/N;
    end
end

```

```

    end

end

%% Combination of medium PRFs

% Based on pulse-to-pulse switching method, how many times
each PRF is going to be used is calculated. The total
number must be equal to the total number of pulses N.
Ambiguity values with regard to the chosen PRFs are then
combined according to the previously obtained matrix.

spcfc_PRI_delay=PRI.*p_sw(haldun3);    %PRI * number of
pulses for this PRI
cum_delay(haldun3+1)=cum_delay(haldun3)+spcfc_PRI_delay;

    while cum_delay(haldun3+1)>delay(beta)
        beta=beta+1;
    end
X_final(:,(alpha+1:beta-1))=X(:,(alpha+1:beta-1));
alpha=beta-1;
%
%
% Each calculated separately for plots

figure(haldun3)
subplot(1,2,1)
mesh(delay.*1e6,fd./1e3,X)
xlabel('Delay ( \musec )'),ylabel('Doppler ( kHz )'),
zlabel('|X|')
title([num2str(N),' pulses, pulse width,
t_p=',num2str(pulsewidth(haldun3).*1e6),' \musec ,
PRI=',num2str(PRI.*1e6) ' \musec '])
subplot(1,2,2)
contour(delay.*1e6,fd./1e3,X)
xlabel('Delay ( \musec )'),ylabel('Doppler ( kHz )')
title(['PRF = ',num2str(PRF(haldun3)./1e3),' kHz '])

figure(length(PRF)+1)
subplot(length(PRF),1,haldun3)
contour(delay.*1e6,fd./1e3,X)
ylabel([num2str(PRF(haldun3)./1e3),' kHz'])

```

```

end

%%

save HALDUN_NO_CLUT

%% plot

figure(length(PRF)+2)
mesh(delay.*1e6,fd./1e3,X_final)
xlabel('Delay ( \musec )'),ylabel('Doppler ( kHz )'),
zlabel('|X|')
title(['Ambiguity Diagram - No Clutter Performance of
',num2str(useprf),' combined MPRFs'])

figure(length(PRF)+3)
contour(delay.*1e6,fd./1e3,X_final)
xlabel('Delay ( \musec )'),ylabel('Doppler ( kHz )')
title(['Ambiguity Contours - No Clutter Performance of
',num2str(useprf),' combined MPRFs'])

```

APPENDIX D

```
% SCR_grz.m

% This program shows the relation between the
% grazing angle and the distance. In addition
% it produces 2 extra plots, showing the relation
% between SCR vs. distance and SCR vs. time delay

clear
clc
sigmat=5;      %target RCS (m^2)
sigma0=10^(-28.8/10); %Backscatter coefficient
h=3000;       %Altitude (m)
HPBW=deg2rad(3.3); %HPBW (radians)
dist=linspace(0,185200,601); %Distance (0-185200 m)
(0-100 nmi)
delay=2.*dist./3e8;
SCR=(sigmat*4*h)./(sigma0*pi.*(h^2+dist.^2).*HPBW);
SCR_dB=10.*log10(SCR);
graze_rad=asin(h./sqrt(h^2+dist.^2));
graze_deg=rad2deg(graze_rad);
figure(1)
plot(dist./1852,graze_deg,'m-')
title('Grazing Angle ( degrees ) vs. Distance ( nmi )')
xlabel('Distance ( nmi )')
ylabel('Grazing Angle ( degrees )')
grid on
figure(2)
subplot(2,1,1)
plot(dist./1852,SCR_dB)
grid on
title('SCR ( dB ) vs. Distance ( nmi )')
xlabel('Distance ( nmi )')
ylabel('SCR ( dB )')
subplot(2,1,2)
plot(delay.*1e6,SCR_dB,'r-')
grid on
title('SCR ( dB ) vs. Time Delay ( \musec )')
xlabel('Time Delay ( \musec )')
ylabel('SCR ( dB )')
axis([0 1236 15 -25])
```

```

% SCR_height.m

% This program shows the relation between
% height and SCR, keeping all other
% variables constant.

clear all
clc

tRCS=5;           %Target RCS in m^2
graze=90;         %grazing angle - degrees
coef_dB=-28.8;   %Backscatter coefficient in dB
coef=10^(coef_dB/10);
halfbw=3.3;      %Halfpower beamwidth- degrees

h=0:3000;        %height-m

Ac=(pi.*(h.*deg2rad(halfbw)).^2)./(4*sin(deg2rad(graze)));
%Clutter area

SCR=tRCS./(coef.*Ac);
SCR_db=10.*log10(SCR); %Signal-to-clutter ratio in dB

plot(h.*3.28,SCR_db)
title('SCR ( dB ) vs. Height (ft)')
xlabel('Height (ft)')
ylabel('SCR ( dB )')
grid on

```



```

% SCR_HP BW.m

% This program shows the relation between HPBW and SCR
% keeping all other variables constant.

clear all
clc

tRCS=5;           %Target RCS in m^2
graze=90;        %grazing angle - degrees
coef_dB=-28.8;   %Backscatter coefficient in dB
coef=10^(coef_dB/10);
halfbw=0:0.1:90;           %Halfpower beamwidth- degrees

h=1500;          %height-m

Ac=(pi.*(h.*deg2rad(halfbw)).^2)./(4*sin(deg2rad(graze)));
%Clutter area

SCR=tRCS./(coef.*Ac);
SCR_db=10.*log10(SCR);   %Signal-to-clutter ratio in dB

plot(halfbw,SCR_db)
title('SCR ( dB ) vs. HPBW (degrees)')
xlabel('HPBW (degrees)')
ylabel('SCR ( dB )')
grid on

```

```

% SCR_TRCS.m

% This program shows the relation between target RCS and
SCR
% keeping all other variables constant.

clear all
clc

tRCS=3:1:100;           %Target RCS in m^2
graze=90;              %grazing angle - degrees
coef_dB=-28.8;        %Backscatter coefficient in dB
coef=10^(coef_dB/10);
halfbw=3.3;           %Halfpower beamwidth- degrees

h=1500;               %height-m

Ac=(pi*(h*deg2rad(halfbw))^2)/(4*sin(deg2rad(graze)));
%Clutter area

SCR=tRCS./(coef*Ac);
SCR_db=10.*log10(SCR); %Signal-to-clutter ratio in dB

plot(tRCS,SCR_db)
title('SCR ( dB ) vs. Target RCS (m^2)')
xlabel('Target RCS (m^2)')
ylabel('SCR ( dB )')
grid on

```

APPENDIX E

```
%*****%
%
% clut.m %
%
% Use: To calculate ambiguity function for each %
%       of the selected PRFs in a clutter %
%       environment and create a combined PRF %
%       sequence with regard to user queried %
%       parameters using function "clut_func" %
%
% Inputs: -PRF Values (Hz) %
%          -Number of PRFs %
%          -Operating Frequency (Hz) %
%          -Constant Duty Cycle %
%          -Minimum Velocity (knots) %
%          -Maximum Velocity (knots) %
%          -Maximum Distance (nmi) %
%          -Number of Pulses %
%          -Target RCS (m^2) %
%          -Backscatter Coefficient (dB) %
%          -Altitude (ft) %
%          -HPBW (degrees) %
%
% Output: -Ambiguity values of each PRF and the %
%          combined sequence. %
%          -Ambiguity diagram and contour plots %
%          of the outputs %
%          -An ambiguity contour comparison plot %
%          that contains all of the individual %
%          plots of each PRF %
%*****%

clear all
close all
clc

%% Default Parameters
```

```

useprf=8;           % Number of PRFs that will be used
f=10e9;            % Operating frequency (Hz)
dc=0.2;           % Constant Duty cycle
vrmin=55;         % Minimum radial velocity (knots)
vrmax=1000;       % Maximum radial velocity (knots)
dmax=100;         % Maximum distance (nmi)
N=15;             % Number of pulses
sigmat=5;         % Target radar cross-section (m^2)
sigma0=-28.8;     % Backscatter coefficient (dB)
altitude=9000;    % Altitude (ft)
hpbw=3.3;         % Half power beamwidth (degrees)
PRF=[30e3  27e3  24e3  20e3  18e3  15e3  13e3  10e3]; %PRF
sequence

```

```
%% Main menu
```

```

newvar=1;
while newvar==1
    clc

```

```

display('*****
*****');
    display('*****
*****');
    display('*****                                PARAMETERS
*****');
    display('*****
*****');

```

```

display('*****
*****');
    display(' ');
    display(['1.   PRF   Sequence   (kHz)   ----->
',num2str(PRF./1e3)]); %default values
    display(['2.   Number   of   PRFs   ----->
',num2str(useprf)]);
    display(['3.   Operating   Frequency   (GHz)   ----->
',num2str(f/1e9)]);
    display(['4.   Constant   Duty   Cycle   ----->
',num2str(dc)]);
    display(['5.   Minimum   Velocity   (knots)   ----->
',num2str(vrmin)]);
    display(['6.   Maximum   Velocity   (knots)   ----->
',num2str(vrmax)]);
    display(['7.   Maximum   Distance   (nmi)   ----->

```

```

',num2str(dmax)]);
    display(['8.   Number   of   Pulses   ----->
',num2str(N)]);
    display(['9.   Target   RCS   (m^2)   ----->
',num2str(sigmat)]);
    display(['10.  Backscatter   Coefficient   (dB)   --->
',num2str(sigma0)]);
    display(['11.  Altitude   (ft)   ----->
',num2str(altitude)]);
    display(['12.  HPBW   (degrees)   ----->
',num2str(hpbw)]);
    display('13. No change. Run the program');
    display(' ');
    display('What would you like to change?');
    display(' ');

    ch_par=input('Please enter a number (1-13) -----> ');
    display(' ');

```

`%% Set New Parameters - Menu Options`

```
switch ch_par
```

```

    case 1 %Set new PRFs
        clc
        for j=1:useprf
            PRF(1,j)=input(['Enter PRF #',num2str(j),' in
Hz (i.e. 10e3) -----> ']);
            while PRF(1,j)<=0 %Error check
                display(' ');
                display('%%%%%%%%%% Please enter a
positive PRF value %%%%%%%%%%%');
                display(' ');
                PRF(1,j)=input(['Enter PRF #',num2str(j),'
in Hz (i.e. 10e3) -----> ']);
            end
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');

```

```

        menu_opt=input('Please choose 1 or 2 ----->
');
    while menu_opt~=1 & menu_opt~=2 %Error check
        display(' ');
        menu_opt=input('Please choose 1 or 2 -----
--> ');
    end
    if menu_opt==2
        newvar=2;
    end
    case 2 %Set new number of PRFs
        clc
        useprf=input('Enter the number of medium PRFs (i.e.
8) -----> ');
        while useprf<=0 | useprf>N %Error check
            display(' ');
            display(['%%%%%           Please enter a positive
value smaller than the number of pulses (',num2str(N),'
%%%%%']);
            display(' ');
            useprf=input('Enter the number of medium PRFs
(i.e. 8) -----> ');
        end

        clc
        clear PRF
        for j=1:useprf
            PRF(1,j)=input(['Enter PRF #',num2str(j),' in
Hz (i.e. 10e3) -----> ']);
            while PRF(1,j)<=0 %Error check
                display(' ');
                display('%%%%%%%%%           Please enter a
positive PRF value  %%%%%%%%%%');
                display(' ');
                PRF(1,j)=input(['Enter PRF #',num2str(j),'
in Hz (i.e. 10e3) -----> ']);
            end
        end
    end
    display(' ');
    display('What would you like to do next?');
    display(' ');
    display('1. Return to main menu');
    display('2. Run the program');
    display(' ');

```

```

        menu_opt=input('Please choose 1 or 2 ----->
');
        while menu_opt~=1 & menu_opt~=2 %Error check
            display(' ');
            menu_opt=input('Please choose 1 or 2 -----
--> ');
        end
        if menu_opt==2
            newvar=2;
        end
        case 3 %Set new operating frequency
            clc
            f=input('Enter Operating Frequency in Hz (i.e.
10e9) -----> ');
            while f<=0
                display(' ');
                display('%%%%%%%%%% Please enter a positive
number %%%%%%%%%%');
                display(' ');
                f=input('Enter Operating Frequency in Hz (i.e.
10e9) -----> ');
            end
            display(' ');
            display('What would you like to do next?');
            display(' ');
            display('1. Return to main menu');
            display('2. Run the program');
            display(' ');
            menu_opt=input('Please choose 1 or 2 ----->
');
            while menu_opt~=1 & menu_opt~=2 %Error check
                display(' ');
                menu_opt=input('Please choose 1 or 2 -----
--> ');
            end
            if menu_opt==2
                newvar=2;
            end

        case 4 %Set new constant duty cycle
            clc
            dc=input('Enter Constant Duty Cycle Between 0 and 1
(i.e. 0.2) ----> ');

```

```

while dc<0 | dc>1 % Error check
    display(' ');
    display('%%%%%%%%%% Please enter a number
between 0 and 1 %%%%%%%%%%');
    display(' ');
    dc=input('Enter Constant Duty Cycle Between 0
and 1 (i.e. 0.2) ----> ');
end
display(' ');
display('What would you like to do next?');
display(' ');
display('1. Return to main menu');
display('2. Run the program');
display(' ');
menu_opt=input('Please choose 1 or 2 ----->
');
while menu_opt~=1 & menu_opt~=2 %Error check
    display(' ');
    menu_opt=input('Please choose 1 or 2 -----
--> ');
end
if menu_opt==2
    newvar=2;
end

case 5 %Set new minimum velocity (knots)
    clc
    vrmin=input('Enter Min. Radial Velocity in knots
(i.e. 55) -----> ');
    while vrmin<0 | vrmin>=vrmax %Error check
        display(' ');
        display(['%%%%%%%%% Please enter a positive
number smaller than max. radial velocity
(',num2str(vrmax),') %%%%%%%%%%']);
        display(' ');
        vrmin=input('Enter Min. Radial Velocity in
knots (i.e. 55) -----> ');
    end
    display(' ');
    display('What would you like to do next?');
    display(' ');
    display('1. Return to main menu');
    display('2. Run the program');

```



```

display(' ');
menu_opt=input('Please choose 1 or 2 ----->
');
while menu_opt~=1 & menu_opt~=2 %Error check
    display(' ');
    menu_opt=input('Please choose 1 or 2 -----
--> ');
end
if menu_opt==2
    newvar=2;
end

case 6 %Set new maximum velocity (knots)
    clc
    vrmax=input('Enter Max. Radial Velocity in knots
(i.e. 1000) -----> ');
    while vrmax<0 | vrmax<=vrmin %Error check
        display(' ');
        display(['%%%%%%%% Please enter a positive
number greater than min. radial velocity
(',num2str(vrmin),') %%%%%%%%%']);
        display(' ');
        vrmax=input('Enter Max. Radial Velocity in
knots (i.e. 1000) -----> ');
    end
    display(' ');
    display('What would you like to do next?');
    display(' ');
    display('1. Return to main menu');
    display('2. Run the program');
    display(' ');
    menu_opt=input('Please choose 1 or 2 ----->
');
while menu_opt~=1 & menu_opt~=2 %Error check
    display(' ');
    menu_opt=input('Please choose 1 or 2 -----
--> ');
end
if menu_opt==2
    newvar=2;
end

```

```

    case 7 % Set new maximum distance
        clc
        dmax=input('Enter Max. Distance in nmi (i.e. 100) -
        -----> ');
        while dmax<=0 %Error check
            display(' ');
            display('%%%%%%%%% Please enter a
positive number %%%%%%%%%');
            display(' ');
            dmax=input('Enter Max. Distance in nmi (i.e.
100) -----> ');
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
');
        while menu_opt~=1 & menu_opt~=2 %Error check
            display(' ');
            menu_opt=input('Please choose 1 or 2 -----
--> ');
        end
        if menu_opt==2
            newvar=2;
        end

    case 8 % Set new number of pulses
        clc
        N=input('Enter Number of Pulses (i.e. 15) -----
        -----> ');
        while N<0 | N<useprf %Error check
            display(' ');
            display(['%%%%%%%%% Please enter a positive
number greater than the number of PRFs
(',num2str(useprf),') %%%%%%%%%']);
            display(' ');
            N=input('Enter Number of Pulses (i.e. 15) -----
        -----> ');
        end
        display(' ');

```

```

display('What would you like to do next?');
display(' ');
display('1. Return to main menu');
display('2. Run the program');
display(' ');
menu_opt=input('Please choose 1 or 2 ----->
');
while menu_opt~=1 & menu_opt~=2 %Error check
    display(' ');
    menu_opt=input('Please choose 1 or 2 -----
--> ');
end
if menu_opt==2
    newvar=2;
end

case 9 % Set new target RCS
    clc
    sigmat=input('Enter Target Radar Cross Section in
m^2 (i.e. 5) -----> ');
    while sigmat<0 %Error check
        display(' ');
        display('%%%%%%%%%% Please enter a
positive number %%%%%%%%%%');
        display(' ');
        sigmat=input('Enter Target Radar Cross Section
in m^2 (i.e. 5) -----> ');
    end
    display(' ');
    display('What would you like to do next?');
    display(' ');
    display('1. Return to main menu');
    display('2. Run the program');
    display(' ');
    menu_opt=input('Please choose 1 or 2 ----->
');
while menu_opt~=1 & menu_opt~=2 %Error check
    display(' ');
    menu_opt=input('Please choose 1 or 2 -----
--> ');
end
if menu_opt==2
    newvar=2;
end

```

```

end

case 10 % Set new backscatter coefficient
    clc
    sigma0=input('Enter Backscatter Coefficient in dB
(i.e. -28.8) -----> ');
    display(' ');
    display('What would you like to do next?');
    display(' ');
    display('1. Return to main menu');
    display('2. Run the program');
    display(' ');
    menu_opt=input('Please choose 1 or 2 ----->
');
    while menu_opt~=1 & menu_opt~=2 %Error check
        display(' ');
        menu_opt=input('Please choose 1 or 2 -----
--> ');
    end
    if menu_opt==2
        newvar=2;
    end

case 11 % Set new altitude
    clc
    altitude=input('Enter Altitude in feet (i.e. 9000)
-----> ');
    while altitude<=0 %Error check
        display(' ');
        display('%%%%%%%%%% Please enter a value
greater than zero %%%%%%%%%%');
        display(' ');
        altitude=input('Enter Altitude in feet (i.e.
9000) -----> ');
    end
    display(' ');
    display('What would you like to do next?');
    display(' ');
    display('1. Return to main menu');
    display('2. Run the program');
    display(' ');
    menu_opt=input('Please choose 1 or 2 ----->

```

```

');
    while menu_opt~=1 & menu_opt~=2 %Error check
        display(' ');
        menu_opt=input('Please choose 1 or 2 -----
--> ');
    end
    if menu_opt==2
        newvar=2;
    end

    case 12 % Set new HPBW
        clc
        hpbw=input('Enter HPBW in degrees (i.e. 3.3) -----
-----> ');
        while hpbw<0 | hpbw>360 %Error check
            display(' ');
            display('%%%%%%%%%% Please enter a value
between 0 and 360 %%%%%%%%%%');
            display(' ');
            hpbw=input('Enter HPBW in degrees (i.e. 3.3) --
-----> ');
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
');
    while menu_opt~=1 & menu_opt~=2 %Error check
        display(' ');
        menu_opt=input('Please choose 1 or 2 -----
--> ');
    end
    if menu_opt==2
        newvar=2;
    end

    case 13 %Run the program
        newvar=2;

```

```

        otherwise
            clc
            newvar=1;

end
end

%%
clc
display( '\ ');
display( '\%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%\
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display( '\%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%\
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display( '\%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%           PLEASE   WAIT
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display( '\%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%\
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display( '\%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%           COMPUTING   ...
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display( '\%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%\
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display( '\%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%\
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display( '\%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%\
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display( '\ ');

%%

X_TOT=clut_func(PRF,useprf,f,dc,vrmin,vrmax,dmax,N,sigmat,s
igma0,altitude,hpbw);

%%

load HALDUN_CLUT.mat

```

```

%*****%
%
% clut_func.m
%
% Use:  To calculate ambiguity function for each
%       of the selected PRFs in a clutter
%       environment and create a combined PRF
%       sequence with regard to user queried
%       parameters
%
% Inputs:  -PRF Values (Hz)
%          -Number of PRFs
%          -Operating Frequency (Hz)
%          -Constant Duty Cycle
%          -Minimum Velocity (knots)
%          -Maximum Velocity (knots)
%          -Maximum Distance (nmi)
%          -Number of Pulses
%          -Target RCS (m^2)

```

```

%           -Backscatter Coefficient (dB)           %
%           -Altitude (ft)                         %
%           -HPBW (degrees)                       %
%
% Output:    -Ambiguity values of each PRF and     %
%            the combined sequence.                %
%           -Ambiguity diagram and contour plots  %
%            of the outputs.                       %
%           -An ambiguity contour comparison      %
%            plot that contains all of the        %
%            individual plots of each PRF        %
%
%*****%
function
X_TOT=clut_func(PRF,useprf,f,dc,vrmin,vrmax,dmax,N,sigmat,s
igma0,altitude,hpbw)

%% Computation

c=3e8;    % speed of light
lambda=c/f;    % wavelength
p=[-(N-1):(N-1)];

%% Doppler Frequency

vr=linspace(vrmin*0.51444445,vrmax*0.51444445,300); %Radial
velocity interval
doppler=2.*vr/lambda;
for haldun2=1:300
    dop_fr(1,haldun2)=doppler(1,(301-haldun2));
end
fd=[-dop_fr 0 doppler]; %Doppler frequencies

%% Time delay
dmin=0;
delaymin=0;
delaymax=2*1852*dmax/c;
delay=linspace(delaymin,delaymax,601); %time delay

%% Clutter Computation

```



```

distance=linspace(dmin*1852,dmax*1852,601);

SCR=(sigmat*4*altitude*0.3048)./(10^(sigma0/10)*pi.*((altitude*0.3048)^2+distance.^2).*deg2rad(hpbw));
SCR_dB=10.*log10(SCR);

for haldun3=1:length(SCR_dB) %Truncating positive SCR values
    if SCR_dB(haldun3)>0
        SCR_dB(haldun3)=0;
    else SCR_dB(haldun3)=SCR_dB(haldun3);
    end
end

SCR_dB_mat=ones(601,1)*SCR_dB;

%% Pulse to pulse switching

p_sw=ones(1,useprf);
tot_p_sw=sum(p_sw);

    for haldun4=1:useprf
        if tot_p_sw~=N
            p_sw(haldun4)=p_sw(haldun4)+1;
            end
        tot_p_sw=sum(p_sw);
    end

%% Ambiguity Function of a Pulse Train
PRI_list=1./PRF;

X_TOT=zeros(601,601);

alpha=0;
beta=1;
cum_delay=zeros(1,length(PRI_list)+1);
X_final=zeros(601,601);

for haldun6=1:length(PRI_list)
    PRI=PRI_list(haldun6);
    pulsewidth(haldun6)=PRI.*dc;
for i=1:length(fd)
    for k=1:length(delay)

```

```

sumtot=0;

for n=1:length(p)
    A=1-abs(delay(k)-p(n)*PRI)/pulsewidth(haldun6);
    Xc=A;

    if abs(pi*pulsewidth(haldun6)*A*fd(i))>1e-4

Xc=abs(A*sin(pi*pulsewidth(haldun6)*A*fd(i))/(pi*pulsewidth
(haldun6)*A*fd(i)));
    end

    B=0;
    if abs(delay(k)-p(n)*PRI)<=pulsewidth(haldun6)
    B=N-abs(p(n));

    if abs(sin(pi*fd(i)*PRI))>1e-5
        B=sin(pi*fd(i)*(N-
abs(p(n))*PRI)/sin(pi*fd(i)*PRI);
    end

    end
    sumtot=sumtot+abs(B)*Xc;

    end
X(i,k)=sumtot/N;

end

end

%% Combination of medium PRFs

% Based on pulse-to-pulse switching method, how
% many times each PRF is going to be used is
% calculated.The total number must be equal to the
% total number of pulses N. Ambiguity values with
% regard to the chosen PRFs are then combined
% according to the previously obtained matrix.

spcfc_PRI_delay=PRI.*p_sw(haldun6);          %PRI * number of
pulses for this PRI
cum_delay(haldun6+1)=cum_delay(haldun6)+spcfc_PRI_delay;

```

```

        while cum_delay(haldun6+1)>delay(beta)
            beta=beta+1;
        end
X_final(:,(alpha+1:beta-1))=X(:,(alpha+1:beta-1));
alpha=beta-1;
%
%
% Each calculated separately for plots
X_sep_dB=10.*log10(X);
X_clu_sep_dB=X_sep_dB+SCR_dB_mat;
X_TOT_sep=10.^(X_clu_sep_dB./10);

figure(haldun6)
subplot(1,2,1)
mesh(delay.*1e6,fd./1e3,X_TOT_sep)
xlabel('Delay ( \musec )'),ylabel('Doppler ( kHz )'),
zlabel('|X|')
title([num2str(N),'          pulses,          pulse          width,
t_p=',num2str(pulsewidth(haldun6).*1e6),'          \musec          ,
PRI=',num2str(PRI.*1e6) ' \musec '])
subplot(1,2,2)
contour(delay.*1e6,fd./1e3,X_TOT_sep)
xlabel('Delay ( \musec )'),ylabel('Doppler ( kHz )')
title(['PRF = ',num2str(PRF(haldun6)./1e3),' kHz '])

figure(length(PRF)+1)
subplot(length(PRF),1,haldun6)
contour(delay.*1e6,fd./1e3,X_TOT_sep)
ylabel([num2str(PRF(haldun6)./1e3),' kHz'])

end
X_dB=10.*log10(X_final); %Ambiguity values are converted to
dB
X_clutter_dB=X_dB+SCR_dB_mat; %Clutter is added to the
ambiguity values
X_TOT=10.^(X_clutter_dB./10); %The output is converted to a
numerical value

%%

save HALDUN_CLUT

```

```

%% plot

figure(length(PRF)+2)
mesh(delay.*1e6,fd./1e3,X_TOT)
xlabel('Delay ( \musec )'),ylabel('Doppler ( kHz )'),
zlabel('|X|')
title(['Ambiguity Diagram - Clutter Performance of
',num2str(useprf),' combined MPRFs'])

figure(length(PRF)+3)
contour(delay.*1e6,fd./1e3,X_TOT)
xlabel('Delay ( \musec )'),ylabel('Doppler ( kHz )')
title(['Ambiguity Contours - Clutter Performance of
',num2str(useprf),' combined MPRFs'])

```

APPENDIX F

```
%*****%
%
% mprf.m
%
% Use: To find localized optimum selection of
%      medium PRFs with regard to user
%      queried parameters using function
%      "mprf_opt_func"
%
% Inputs:  -Minimum PRF Value (Hz)
%          -Maximum PRF Value (Hz)
%          -Number of PRFs
%          -Operating Frequency (Hz)
%          -Constant Duty Cycle
%          -Minimum Velocity (knots)
%          -Maximum Velocity (knots)
%          -Maximum Distance (nmi)
%          -Number of Pulses
%          -Target RCS (m^2)
%          -Backscatter Coefficient (dB)
%          -Altitude (ft)
%          -HPBW (degrees)
%          -Number of Iterations
%
% Output:  -Localized Optimum selection of
%          Medium PRFs within the specified
%          interval after given number of
%          iterations
%          -Ambiguity diagram and contour
%          plots of the output
%
%*****%

clear all
close all
clc

%% Default Parameters

prfmin=10e3;      % Minimum PRF value (Hz)
```

```

prfmax=30e3;           % Maximum PRF value (Hz)
useprf=8;             % Number of PRFs that will be used
f=10e9;              % Operating frequency (Hz)
dc=0.2;              % Constant Duty cycle
vrmin=55;            % Minimum radial velocity (knots)
vrmax=1000;          % Maximum radial velocity (knots)
dmax=100;            % Maximum distance (nmi)
N=50;                % Number of pulses
sigmat=5;            % Target radar cross-section (m^2)
sigma0=-28.8;        % Backscatter coefficient (dB)
altitude=9000;       % Altitude (ft)
hpbw=3.3;            % Half power beamwidth (degrees)
numit=300;           % Number of iterations

%% Main menu
newvar=1;
while newvar==1
    clc

    display('*****');
    display('*****');
    display('*****')           PARAMETERS
    display('*****');
    display('*****');

    display('*****');
    display(' ');
    display(['1.  Minimum PRF Value (kHz) ----->
',num2str(prfmin./1e3)]; %default values
    display(['2.  Maximum PRF Value (kHz) ----->
',num2str(prfmax./1e3)];
    display(['3.  Number of PRFs ----->
',num2str(useprf)]);
    display(['4.  Operating Frequency (GHz) ----->
',num2str(f/1e9)]);
    display(['5.  Constant Duty Cycle ----->
',num2str(dc)]);
    display(['6.  Minimum Velocity (knots) ----->
',num2str(vrmin)]);
    display(['7.  Maximum Velocity (knots) ----->

```

```

',num2str(vrmax)]);
    display(['8. Maximum Distance (nmi) ----->
',num2str(dmax)]);
    display(['9. Number of Pulses ----->
',num2str(N)]);
    display(['10. Target RCS (m^2) ----->
',num2str(sigmat)]);
    display(['11. Backscatter Coefficient (dB) ---->
',num2str(sigma0)]);
    display(['12. Altitude (ft) ----->
',num2str(altitude)]);
    display(['13. HPBW (degrees) ----->
',num2str(hpbw)]);
    display(['14. Number of Iterations ----->
',num2str(numit)]);
    display('15. No change. Run the program');
    display(' ');
    display('What would you like to change?');
    display(' ');

    ch_par=input('Please enter a number (1-15) -----> ');
    display(' ');

```

```

%% Set New Parameters - Menu Options

```

```

switch ch_par

```

```

    case 1 %Set new min PRF
        clc
        prfmin=input('Enter the min. value of medium PRF in
Hz (i.e. 10e3) -----> ');
        while prfmin>prfmax | prfmin<=0 %Error check
            display(' ');
            display('%%%%%%%%%% Please enter a PRF
value smaller than the maximum PRF value
%%%%%%%%%%');
            display(['%%%%%%%%%%
Maximum PRF value is ',num2str(prfmax),' Hz
%%%%%%%%%%']);
            display(' ');
            prfmin=input('Enter the min. value of medium
PRF in Hz (i.e. 10e3) -----> ');
        end

```

```

display(' ');
display('What would you like to do next?');
display(' ');
display('1. Return to main menu');
display('2. Run the program');
display(' ');
menu_opt=input('Please choose 1 or 2 ----->
');
while menu_opt~=1 & menu_opt~=2 %Error check
    display(' ');
    menu_opt=input('Please choose 1 or 2 -----
--> ');
end
if menu_opt==2
    newvar=2;
end

case 2 %Set new max PRF
    clc
    prfmax=input('Enter the max. value of medium PRF in
Hz (i.e. 30e3) -----> ');
    while prfmax<prfmin | prfmax<=0 %Error check
        display(' ');
        display('%%%%%%%%%% Please enter a PRF
value greater than the minimum PRF value
%%%%%%%%%%');
        display(['%%%%%%%%%%
Minimum PRF value is ',num2str(prfmin),' Hz
%%%%%%%%%%']);
        display(' ');
        prfmax=input('Enter the max. value of medium
PRF in Hz (i.e. 30e3) -----> ');
    end
    display(' ');
    display('What would you like to do next?');
    display(' ');
    display('1. Return to main menu');
    display('2. Run the program');
    display(' ');
    menu_opt=input('Please choose 1 or 2 ----->
');
while menu_opt~=1 & menu_opt~=2 %Error check
    display(' ');

```



```

        menu_opt=input('Please choose 1 or 2 -----
--> ');
    end
    if menu_opt==2
        newvar=2;
    end

    case 3 %Set new number of PRFs
        clc
        useprf=input('Enter the number of medium PRFs (i.e.
8) -----> ');
        while useprf<=0 | useprf>N %Error check
            display(' ');
            display(['%%%% Please enter a positive
value smaller than the number of pulses (',num2str(N),'
%%%%']);
            display(' ');
            useprf=input('Enter the number of medium PRFs
(i.e. 8) -----> ');
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
');
        while menu_opt~=1 & menu_opt~=2 %Error check
            display(' ');
            menu_opt=input('Please choose 1 or 2 -----
--> ');
        end
        if menu_opt==2
            newvar=2;
        end

    case 4 %Set new operating frequency
        clc
        f=input('Enter Operating Frequency in Hz (i.e.
10e9) -----> ');
        while f<=0

```

```

        display(' ');
        display('%%%%%%%%%% Please enter a positive
number %%%%%%%%%');
        display(' ');
        f=input('Enter Operating Frequency in Hz (i.e.
10e9) -----> ');
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
');
        while menu_opt~=1 & menu_opt~=2 %Error check
            display(' ');
            menu_opt=input('Please choose 1 or 2 -----
--> ');
        end
        if menu_opt==2
            newvar=2;
        end

        case 5 %Set new constant duty cycle
            clc
            dc=input('Enter Constant Duty Cycle Between 0 and 1
(i.e. 0.2) ----> ');
            while dc<0 | dc>1 % Error check
                display(' ');
                display('%%%%%%%%%% Please enter a number
between 0 and 1 %%%%%%%%%');
                display(' ');
                dc=input('Enter Constant Duty Cycle Between 0
and 1 (i.e. 0.2) ----> ');
            end
            display(' ');
            display('What would you like to do next?');
            display(' ');
            display('1. Return to main menu');
            display('2. Run the program');
            display(' ');
            menu_opt=input('Please choose 1 or 2 ----->

```

```

');
    while menu_opt~=1 & menu_opt~=2 %Error check
        display(' ');
        menu_opt=input('Please choose 1 or 2 -----
--> ');
    end
    if menu_opt==2
        newvar=2;
    end

    case 6 %Set new minimum velocity (knots)
        clc
        vrmin=input('Enter Min. Radial Velocity in knots
(i.e. 55) -----> ');
        while vrmin<0 | vrmin>=vrmax %Error check
            display(' ');
            display(['%%%%%%%%% Please enter a positive
number smaller than max. radial velocity
(',num2str(vrmax),') %%%%%%%%%%']);
            display(' ');
            vrmin=input('Enter Min. Radial Velocity in
knots (i.e. 55) -----> ');
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
');
        while menu_opt~=1 & menu_opt~=2 %Error check
            display(' ');
            menu_opt=input('Please choose 1 or 2 -----
--> ');
        end
        if menu_opt==2
            newvar=2;
        end

        case 7 %Set new maximum velocity (knots)
            clc

```

```

        vrmax=input('Enter Max. Radial Velocity in knots
(i.e. 1000) -----> ');
        while vrmax<0 | vrmax<=vrmin %Error check
            display(' ');
            display(['%%%%%%%%% Please enter a positive
number greater than min. radial velocity
(',num2str(vrmin),') %%%%%%%%%%']);
            display(' ');
            vrmax=input('Enter Max. Radial Velocity in
knots (i.e. 1000) -----> ');
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
');
        while menu_opt~=1 & menu_opt~=2 %Error check
            display(' ');
            menu_opt=input('Please choose 1 or 2 -----
--> ');
        end
        if menu_opt==2
            newvar=2;
        end

        case 8 % Set new maximum distance
            clc
            dmax=input('Enter Max. Distance in nmi (i.e. 100) -
-----> ');
            while dmax<=0 %Error check
                display(' ');
                display('%%%%%%%%% Please enter a
positive number %%%%%%%%%%');
                display(' ');
                dmax=input('Enter Max. Distance in nmi (i.e.
100) -----> ');
            end
            display(' ');
            display('What would you like to do next?');
            display(' ');

```

```

display('1. Return to main menu');
display('2. Run the program');
display(' ');
menu_opt=input('Please choose 1 or 2 ----->
');
while menu_opt~=1 & menu_opt~=2 %Error check
    display(' ');
    menu_opt=input('Please choose 1 or 2 -----
--> ');
end
if menu_opt==2
    newvar=2;
end

case 9 % Set new number of pulses
    clc
    N=input('Enter Number of Pulses (i.e. 50) -----
-----> ');
    while N<0 | N<useprf %Error check
        display(' ');
        display(['%%%%%%%% Please enter a positive
number greater than the number of PRFs
(',num2str(useprf),') %%%%%%%%%']);
        display(' ');
        N=input('Enter Number of Pulses (i.e. 50) -----
-----> ');
    end
    display(' ');
    display('What would you like to do next?');
    display(' ');
    display('1. Return to main menu');
    display('2. Run the program');
    display(' ');
    menu_opt=input('Please choose 1 or 2 ----->
');
while menu_opt~=1 & menu_opt~=2 %Error check
    display(' ');
    menu_opt=input('Please choose 1 or 2 -----
--> ');
end
if menu_opt==2
    newvar=2;
end

```

```

    case 10 % Set new target RCS
        clc
        sigmat=input('Enter Target Radar Cross Section in
m^2 (i.e. 5) -----> ');
        while sigmat<0 %Error check
            display(' ');
            display('%%%%%%%%%% Please enter a
positive number %%%%%%%%%%');
            display(' ');
            sigmat=input('Enter Target Radar Cross Section
in m^2 (i.e. 5) -----> ');
        end
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
');
        while menu_opt~=1 & menu_opt~=2 %Error check
            display(' ');
            menu_opt=input('Please choose 1 or 2 -----
--> ');
        end
        if menu_opt==2
            newvar=2;
        end

    case 11 % Set new backscatter coefficient
        clc
        sigma0=input('Enter Backscatter Coefficient in dB
(i.e. -28.8) -----> ');
        display(' ');
        display('What would you like to do next?');
        display(' ');
        display('1. Return to main menu');
        display('2. Run the program');
        display(' ');
        menu_opt=input('Please choose 1 or 2 ----->
');

```

```

while menu_opt~=1 & menu_opt~=2 %Error check
    display(' ');
    menu_opt=input('Please choose 1 or 2 -----
--> ');
end
if menu_opt==2
    newvar=2;
end

case 12 % Set new altitude
    clc
    altitude=input('Enter Altitude in feet (i.e. 9000)
-----> ');
    while altitude<=0 %Error check
        display(' ');
        display('%%%%%%%%%% Please enter a value
greater than zero %%%%%%%%%%');
        display(' ');
        altitude=input('Enter Altitude in feet (i.e.
9000) -----> ');
    end
    display(' ');
    display('What would you like to do next?');
    display(' ');
    display('1. Return to main menu');
    display('2. Run the program');
    display(' ');
    menu_opt=input('Please choose 1 or 2 ----->
');
    while menu_opt~=1 & menu_opt~=2 %Error check
        display(' ');
        menu_opt=input('Please choose 1 or 2 -----
--> ');
    end
    if menu_opt==2
        newvar=2;
    end

case 13 % Set new HPBW
    clc
    hpbw=input('Enter HPBW in degrees (i.e. 3.3) -----
-----> ');

```

```

while hpbw<0 | hpbw>360 %Error check
    display(' ');
    display('%%%%%%%%%%%%%% Please enter a value
between 0 and 360 %%%%%%%%%%%%%%');
    display(' ');
    hpbw=input('Enter HPBW in degrees (i.e. 3.3) --
-----> ');
end
display(' ');
display('What would you like to do next?');
display(' ');
display('1. Return to main menu');
display('2. Run the program');
display(' ');
menu_opt=input('Please choose 1 or 2 ----->
');
while menu_opt~=1 & menu_opt~=2 %Error check
    display(' ');
    menu_opt=input('Please choose 1 or 2 -----
--> ');
end
if menu_opt==2
    newvar=2;
end

case 14 % Set new number of iterations
    clc
    numitvar=input('Enter the number of iterations
(i.e. 300) -----> ');
    numit=floor(numitvar);
    while numit<=0 %Error check
        display(' ');
        display('%%%%%%%%%%%%%% Please enter a
positive value %%%%%%%%%%%%%%');
        display(' ');
        numitvar=input('Enter the number of iterations
(i.e. 300) -----> ');
        numit=floor(numitvar);
    end
    display(' ');
    display('What would you like to do next?');
    display(' ');
    display('1. Return to main menu');

```



```

display('2. Run the program');
display(' ');
menu_opt=input('Please choose 1 or 2 ----->
');
while menu_opt~=1 & menu_opt~=2 %Error check
    display(' ');
    menu_opt=input('Please choose 1 or 2 -----
--> ');
end
if menu_opt==2
    newvar=2;
end

case 15 %Run the program
    newvar=2;

otherwise
    clc
    newvar=1;

end
end

%%
clc
display(' ');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% PLEASE WAIT');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% COMPUTING ...');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display(' ');

```

```
%%  
  
X_clutter=mprf_opt_func(prfmin,prfmax,useprf,f,dc,vrmin,vrm  
ax,dmax,N,sigmat,sigma0,altitude,hpbw,numit);
```

```
%%  
  
load HALDUN_LOC_OPT.mat
```

```
*****%  
%  
% mprf_opt_func.m %  
%  
% Use: To find localized optimum selection of %  
% medium PRFs with regard to user %  
% queried parameters %  
%  
% Inputs: -Minimum PRF Value (Hz) %  
% -Maximum PRF Value (Hz) %  
% -Number of PRFs %  
% -Operating Frequency (Hz) %  
% -Constant Duty Cycle %  
% -Minimum Velocity (knots) %  
% -Maximum Velocity (knots) %  
% -Maximum Distance (nmi) %  
% -Number of Pulses %
```

```

%           -Target RCS (m^2)           %
%           -Backscatter Coefficient (dB) %
%           -Altitude (ft)             %
%           -HPBW (degrees)            %
%           -Number of Iterations       %
%           %                           %
% Output:   -Localized Optimum selection of %
%           Medium PRFs within the specified %
%           interval after given number of %
%           iterations                   %
%           -Ambiguity diagram and contour %
%           plots of the output          %
%           %                           %
%*****%

```

```
function
```

```
X_clutter=mprf_opt_func(prfmin,prfmax,useprf,f,dc,vrmin,vrmax,dmax,N,sigmat,sigma0,altitude,hpbw,numit)
```

```
% Creates a random matrix of 1 x number of prfs between min
and max values
% of prf
```

```
for haldun1=1:numit
PRF_sel(haldun1,:)=random('unif',prfmin,prfmax,[1,useprf]);
end
```

```
PRF=floor(PRF_sel);
%% Computation
```

```
c=3e8; % speed of light
lambda=c/f; % wavelength
p=[-(N-1):(N-1)];
```

```
%% Doppler Frequency
```

```
vr=linspace(vrmin*0.51444445,vrmax*0.51444445,300); %Radial
velocity interval
doppler=2.*vr/lambda;
for haldun2=1:300
    dop_fr(1,haldun2)=doppler(1,(301-haldun2));
end
```

```

fd=[-dop_fr 0 doppler]; %Doppler frequencies

%% Time delay
dmin=0;
delaymin=0;
delaymax=2*1852*dmax/c;
delay=linspace(delaymin,delaymax,601); %time delay

%% Clutter Computation

distance=linspace(dmin*1852,dmax*1852,601);

SCR=(sigmat*4*altitude*0.3048)./(10^(sigma0/10)*pi.*((altitude*0.3048)^2+distance.^2).*deg2rad(hpbw));
SCR_dB=10.*log10(SCR);

for haldun3=1:length(SCR_dB) %Truncating positive SCR
values
    if SCR_dB(haldun3)>0
        SCR_dB(haldun3)=0;
    else SCR_dB(haldun3)=SCR_dB(haldun3);
    end
end

SCR_dB_mat=ones(601,1)*SCR_dB;

%% Pulse to pulse switching

p_sw=ones(1,useprf);
tot_p_sw=sum(p_sw);

    for haldun4=1:useprf
        if tot_p_sw~=N
            p_sw(haldun4)=p_sw(haldun4)+1;
            end
            tot_p_sw=sum(p_sw);
        end

%% Ambiguity Function of a Pulse Train
PRI_list_tot=1./PRF;

X_TOT=zeros(601,601*numit);

for haldun5=1:numit

```

```

PRI_list=PRI_list_tot(haldun5,:);

alpha=0;
beta=1;
cum_delay=zeros(1,length(PRI_list)+1);
X_final=zeros(601,601);

for haldun6=1:length(PRI_list)
    PRI=PRI_list(haldun6);
    pulsewidth(haldun6)=PRI.*dc;
    for i=1:length(fd)
        for k=1:length(delay)
            sumtot=0;

            for n=1:length(p)
                A=1-abs(delay(k)-p(n)*PRI)/pulsewidth(haldun6);
                Xc=A;

                if abs(pi*pulsewidth(haldun6)*A*fd(i))>1e-4

Xc=abs(A*sin(pi*pulsewidth(haldun6)*A*fd(i))/(pi*pulsewidth
(haldun6)*A*fd(i)));
                    end

                    B=0;
                    if abs(delay(k)-p(n)*PRI)<=pulsewidth(haldun6)
                        B=N-abs(p(n));

                        if abs(sin(pi*fd(i)*PRI))>1e-5
                            B=sin(pi*fd(i)*(N-
abs(p(n)))*PRI)/sin(pi*fd(i)*PRI);
                        end

                    end

                    sumtot=sumtot+abs(B)*Xc;

                end

            end

            X(i,k)=sumtot/N;

        end

    end

end

```

```

%% Combination of medium PRFs

% Based on pulse-to-pulse switching method, how many times
each PRF is
% going to be used is calculated.The total number must be
equal to the
% total number of pulses N. Ambiguity values with regard to
the chosen PRFs
% are then combined according to the previously obtained
matrix.

spcfc_PRI_delay=PRI.*p_sw(haldun6);          %PRI * number of
pulses for this PRI
cum_delay(haldun6+1)=cum_delay(haldun6)+spcfc_PRI_delay;

    while cum_delay(haldun6+1)>delay(beta)
        beta=beta+1;
    end
    X_final(:,(alpha+1:beta-1))=X(:,(alpha+1:beta-1));
    alpha=beta-1;
end

X_dB=10.*log10(X_final); %Ambiguity values are converted to
dB
X_clutter_dB=X_dB+SCR_dB_mat; %Clutter is added to the
ambiguity values
X_clutter=10.^(X_clutter_dB./10); %The output is converted
to a numerical value
X_TOT(:,((haldun5-1)*601)+1):(haldun5*601))=X_clutter; %
The results for each iteration
% are saved in a bigger matrix,which contains all of the
values

end
%% Comparison
%all of the chosen prf sequences are compared with regard
to their performance.

for haldun7=1:numit %Ambiguity values,all of which are
between 0 and 1, are summed for each
%sequence.

```

```

    all_PRF_X_TOT=sum(X_TOT(:,((haldun7-
1)*601)+1):(haldun7*601)));
    sum_all_PRF_X_TOT=sum(all_PRF_X_TOT);
    tot_ambg_val(haldun7)=sum_all_PRF_X_TOT;
end

% The sequence with the maximum value gives the best
% performance, providing
% the longest detection range
[Y,I]=max(tot_ambg_val);

opt_prf=PRF(I,:);
% I is the number of iteration which the localized optimum
% is reached.

save HALDUN_LOC_OPT

display(' ');
display('The localized optimum selection within the given
set of MPRFs with');
display(['regard to performance is set #',num2str(I)]);
display(' ');
display(opt_prf);
display(' ');

%% Extra

display(' ');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% NOTE');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display('%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%');
display(' ');

```

```

see_all_prf=input(['Would you like to see all of the
\',num2str(numit),' MPRF sequences? (y/Y or n/N) ---->
'],'s');

while see_all_prf~='y' & see_all_prf~='Y' &
see_all_prf~='n' & see_all_prf~='N'
    display(' ');
    display('Please type y/Y or n/N');
    display(' ');
    see_all_prf=input(['Would you like to see all of the
\',num2str(numit),' MPRF sequences? (y/Y or n/N) ---->
'],'s');
end

display(' ');

if see_all_prf=='y' | see_all_prf=='Y'
    display([num2str(numit),' MPRF sequences']);
    PRF
    display(' ');
    display('Thank you for using the program.');
```

beep;

```

else
    display('Thank you for using the program.');
```

beep;

```

end

%% plot

figure(1)
mesh(delay.*1e6,fd./1e3,X_TOT(:,((I-1)*601)+1):(I*601)))
xlabel('Delay ( \musec )'),ylabel('Doppler ( kHz )'),
zlabel('|X|')
title(['Ambiguity Diagram - Localized Optimum Performance
Results of ',num2str(useprf),' MPRFs'])

figure(2)
contour(delay.*1e6,fd./1e3,X_TOT(:,((I-
1)*601)+1):(I*601)))

```



```
xlabel('Delay ( \musec )'),ylabel('Doppler ( kHz )')  
title(['Ambiguity Contours - Localized Optimum Performance  
Results of ',num2str(useprf),' MPRFs'])
```

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APPENDIX G

The 300 MPRF sequences, which are used in the third part of the simulation, are shown below. Each sequence consists of 8 MPRFs and units are in Hz. The localized optimum sequence is highlighted in yellow.

18957	23024	13390	20628	22676	10281	19407	27726
12280	18850	23190	15895	29007	23885	14136	21095
27585	21157	25046	27898	26836	12617	13783	13072
10578	10181	21929	22180	28378	24671	16022	19911
15163	24657	12335	24920	26195	24904	16742	21686
19379	11745	26574	23718	15346	29389	13675	15998
18223	14729	13901	24107	13610	20446	15923	19255
28504	14317	10020	28132	23600	20299	20441	12058
29937	17179	22504	17867	10153	20905	20182	14935
10907	26834	10964	16326	25668	29448	21729	25560
24553	23019	23292	28775	20701	17968	23409	18810
12657	18784	20952	17902	17965	25026	20447	19808
11773	15017	18951	22759	24188	29852	28643	11844
29070	13255	29409	21940	14804	11405	16000	26270
11534	17089	12640	13163	11242	24036	11729	22335
13475	23028	19973	15690	26611	26367	28763	10006
22807	10147	12128	12135	17342	14792	16922	14992
17741	18420	22801	25751	15399	26879	24809	26522
13643	11308	22207	24031	12232	11916	21956	26244
26291	11788	24625	28077	19044	11413	14825	24637
10809	18490	20804	29076	14178	12326	22924	12168
29669	14966	22127	26333	26601	19780	25214	28302
28019	14284	20941	25694	13888	24937	19511	21665
15210	11696	15962	28342	19410	15389	25259	25443
10425	27599	25963	16483	23380	15925	28599	15639
13377	24903	19542	23068	29331	16260	11528	25828
17307	21701	13666	11538	13073	26537	16019	17677
23014	26347	25325	17483	13797	22930	10072	15657
22772	21841	16505	29779	12464	24717	13132	18692
26644	17198	11524	21138	15478	12641	23993	19718
13654	12024	14031	12694	16475	29010	20642	14953
18745	23381	20953	22181	27262	17613	24979	13133
11162	16794	26343	17550	29452	22106	16764	28559
27968	27014	15135	15709	25598	24027	19850	29353
19523	29898	19811	20069	25375	17761	19065	12657
25170	21304	22972	25961	14408	27157	28094	15840

24517	16788	15453	13405	23280	20717	26582	15347
13523	18623	19513	25704	12613	11027	22550	10581
12723	23891	20313	20851	26169	25873	20037	15532
12393	27731	29405	28850	22762	11811	11494	13649
10633	24498	12883	22718	25796	21325	17548	26431
16097	16387	25699	20074	15219	24649	13258	28421
14444	11672	11474	25391	26353	24808	25164	29223
19328	25739	18451	28874	10026	29625	21403	16929
21150	15995	13181	23305	23684	25848	16972	15001
16900	16572	28549	25121	15764	22123	25320	26923
28039	21914	11370	14360	27388	18284	23224	25669
14957	21088	14591	10138	25332	10436	17862	15050
14084	23245	28294	10138	24928	25993	28155	29491
12397	20379	26439	22740	29078	28938	29332	11346
18750	16416	12681	12691	26118	20495	28885	29766
18197	17423	14537	18920	15324	19181	18658	15192
12674	18384	20137	16486	23693	18861	18713	25860
26311	25042	25785	20025	21103	22614	11959	14913
22314	16099	25339	15344	10790	15931	21127	29381
23782	24357	21180	20667	27514	17861	19161	14164
25145	20933	17147	24019	12184	10132	21946	23183
21600	28199	22720	20511	15192	11023	24639	13285
15607	15188	20941	20825	25762	27392	25750	29388
13609	28611	10903	14812	10177	23431	28096	21448
13109	20047	21354	13765	16483	24320	21058	12845
17607	17931	21534	10388	21551	28643	12137	24642
29410	22177	24393	16055	19180	10960	17707	17234
15751	26334	19010	26132	25803	15659	11366	11098
22750	18485	28110	18346	13081	20799	28741	23219
17893	15179	26958	28901	17539	11345	13631	21514
13717	15828	19233	16939	16363	19198	14717	10555
23169	13176	26053	18171	16547	24920	24927	13479
12350	13480	22548	26837	20201	13315	24286	28140
14370	27419	14236	26733	27186	20467	19547	27797
11301	20189	22415	24671	14599	10437	12779	25390
29395	17735	29868	16527	12743	17695	21252	22676
20832	16299	13186	13052	12739	24196	19297	12265
24017	13599	26073	20279	20968	14156	25691	20529
21420	18440	24423	11462	21897	27239	18976	23051
16069	22148	15578	25991	25923	29081	18886	19137
21996	26852	10624	13745	28871	28958	19059	26216
28577	23454	17446	18113	18776	23572	19301	29065
17093	16780	27917	20908	24985	12497	19064	11494
23266	24073	28379	23201	23802	27074	19358	19169
26122	26495	13808	10513	11136	12858	13428	22516

10590	19446	23568	12295	14721	15781	13455	16474
26022	15992	25512	21055	21093	24612	25472	28016
12763	25881	13788	10579	12547	12674	12566	28705
15464	28853	22763	27450	17341	14724	13746	20912
15102	16116	10310	21749	29251	26996	10158	22680
17185	12281	20816	18328	20341	27722	12987	18693
11180	17620	24447	11902	23343	15928	21971	13037
18727	10253	14580	15273	20227	14301	16922	24956
18272	11115	17800	19489	26506	16072	26435	21313
11087	15200	21782	19594	13973	14780	25603	22346
12882	24322	18030	19247	24145	18024	10287	11492
21821	18920	28532	11897	17508	20919	12233	28089
22665	28108	22611	10284	16329	12237	22589	11214
23479	19548	16110	20326	24140	26272	16316	16226
16899	23326	27221	25235	27516	27424	13455	27004
29191	25404	27500	11348	22935	16481	22806	27595
17472	25334	13361	20394	22549	24278	16127	15273
28320	22300	11863	22553	13840	25539	27290	16671
12708	25309	16372	15047	14001	11380	21038	18076
25002	19743	17695	11228	14273	20877	18212	28019
11125	18870	20756	12681	20818	27147	13960	13112
11227	23221	10372	15822	29476	25292	14873	23642
12757	22596	27140	27995	16967	19726	23590	24082
19217	17285	15605	11524	18892	13314	17974	28411
20226	28282	11838	29860	11928	16262	25707	22048
19318	15962	12663	15900	13332	16342	12196	26641
29431	14365	24121	10780	22325	23387	10744	10066
12849	27248	15520	20633	20444	21352	16660	18268
18286	29678	11154	17930	25826	21883	16191	28036
11862	16380	27739	23148	23690	19478	12824	29018
27652	18748	26699	16502	17352	25896	11986	29035
10029	15907	10969	18854	25796	28270	20665	26081
21253	25017	10184	19535	15006	16158	29338	14176
20409	14510	21343	29963	12637	29093	12477	13724
22930	12563	11626	23184	10547	29703	20786	17476
24134	28948	17645	23858	22041	25505	21836	17523
27012	14514	25939	29937	15626	24207	23292	18296
19965	28982	29063	24658	17693	10801	21658	21294
17103	27604	22490	22480	15914	11493	15874	14694
16917	26969	13207	13157	20173	22066	13227	22709
26878	25645	15291	16293	13663	18949	16533	15596
28635	17993	17588	21856	11370	14104	24472	21502
14004	26869	18474	20895	20559	13702	11633	19281
10611	18699	21157	22775	10684	24198	13386	21867
22161	25447	11125	27094	17685	17992	16508	21107

15908	17322	16980	22604	23288	29841	28887	17006
13859	28391	15773	21017	28386	11800	15153	18540
21554	27990	14364	29340	18679	25696	20504	16625
18631	24358	28324	27800	12694	12398	27869	23061
10805	20094	27889	17714	15841	14680	14018	17606
21895	15367	22448	26091	12079	24584	22971	19493
28658	11928	21982	14671	10646	21597	26843	21137
26797	14099	22425	13480	15790	10370	24029	29041
24980	25134	20841	15641	14897	15726	29262	14613
20746	14100	18680	12844	17511	25871	26256	28075
20807	26357	24168	10864	12918	14666	14934	13405
14701	15509	29032	16933	15946	18088	16044	25146
17194	12497	22343	17110	17258	11369	27343	19157
11552	28098	15633	22277	23237	14000	29199	23302
20825	27379	21140	10427	19653	26159	24720	21446
10179	24365	18988	23192	25064	26094	10583	25596
21347	11522	15032	12669	21289	20819	11378	29768
15021	16309	16013	10840	20558	15120	18174	28950
28385	12424	21838	17193	24386	20471	15216	19861
27116	24488	13982	13145	17409	27245	23695	22683
12826	11586	27522	18408	19753	19206	20313	15439
14631	27990	28173	22072	17304	21971	23369	27891
11746	20780	18568	22343	21177	14517	12090	10199
11183	16453	25589	16709	22391	29857	22960	20795
14645	24796	27779	27196	21941	23095	28300	18663
15795	22637	15908	22440	10950	29892	14135	22147
16952	24354	10559	11336	28541	11755	16647	20523
14932	20857	25617	20437	28638	12942	18335	15605
21962	10729	11273	16457	11967	13400	17423	10795
24184	22826	13481	11243	18133	19261	14053	27390
21958	10460	27988	19058	11160	12125	29968	27326
22304	10538	16450	19275	11980	21419	16517	19009
21556	11496	11146	16019	20434	21237	14831	28254
26514	18890	29641	21565	14688	26211	19025	14999
29108	12853	20251	29438	22966	22293	19393	21555
28226	17524	14575	18470	15471	18891	22550	20692
17708	27469	16006	18000	20354	11236	14627	12369
11975	27805	10667	26780	20145	12274	19808	21988
11804	29564	23060	19222	27275	15256	26479	16579
28826	14882	29142	20216	21291	29874	25419	16276
11157	10881	26258	18241	17683	20462	27842	18118
22087	11896	16719	12896	14897	17579	15406	14311
22674	25994	14170	27925	24914	20727	29399	21297
14353	27155	27239	16266	16539	26800	19850	11038
25560	18533	15599	16670	17338	25895	10773	24533

27453	15716	23136	14637	22439	11502	29335	22199
17674	10611	27151	22070	26956	20092	10158	28381
18214	24647	13022	26304	28192	25558	25142	18103
24038	21309	21694	16898	24084	13217	10030	21240
20929	21016	23890	28549	28884	28065	22082	28524
12338	16816	10734	20767	24744	13624	18524	11963
16064	25602	20739	25381	22778	27862	11213	13515
18326	24795	27859	10517	12751	18481	25291	20488
25089	13395	23454	22373	10136	24804	29834	12563
17211	13821	24287	13557	29736	10339	10795	26086
27195	21325	25082	20390	21718	13814	20068	11018
11121	16703	22618	27839	23467	23705	23914	25996
23212	20398	16634	28683	14929	20224	24806	15083
26911	20763	28202	17014	28706	28554	21754	12035
17337	15516	15321	14530	10026	27860	19069	21568
16312	29880	29677	29290	23325	24523	16680	20455
15467	24367	25560	11621	14431	14079	22481	24504
26687	10377	14042	19381	17567	16807	11277	25226
18053	23485	21021	11029	16149	29308	28629	17560
22353	21250	26611	29153	11510	27760	21248	13887
14429	24115	21935	21725	29369	21634	11996	13332
12041	12924	23431	22797	17448	13257	17790	25999
17995	25102	15904	22800	27702	14192	19607	12259
12647	11280	11585	22539	18226	22771	27131	25271
29523	25630	28711	24783	15072	24385	23870	25466
24944	16367	20208	25461	21456	29077	13431	28144
25044	15723	22548	19256	12588	20987	29390	18842
21819	12219	13997	13259	10737	15454	14602	17170
12686	29971	20270	17756	14997	17295	17981	28526
19909	22183	10096	21754	25549	23143	20566	26515
29248	16274	25941	15703	10297	11882	16574	16111
10360	13244	18879	25335	23625	24290	19195	28385
29778	28652	19230	28098	17729	22060	21206	26916
15696	23266	22045	23129	16198	16632	13763	12013
15731	17096	20715	29816	10563	24190	28103	27316
12383	29105	18818	27515	27299	17103	22622	27290
10419	11536	17534	12983	10681	25644	16544	26349
13472	23522	27512	25143	14592	17178	17263	15348
16746	11739	19031	19093	10580	22742	11189	13383
23693	21091	10120	15761	17532	12929	11490	19214
17407	26491	20750	26350	19207	10280	10099	13324
17318	24364	13188	15575	22898	15744	16438	13108
17753	27914	27755	17872	23509	15044	28999	22493
14138	12193	21316	15486	11423	13168	10990	23617
25635	26147	15301	27917	22159	10288	16880	20673

22555	18934	26222	12896	29496	26675	16802	22324
16075	11784	20430	26505	25278	28952	16670	17794
13008	16674	21073	21005	13208	12341	17971	26627
13700	20015	12526	27292	25332	21287	17791	19802
27738	28100	19967	20584	28194	21571	25515	23227
19393	14395	22051	13685	13950	27239	12512	22911
18746	22252	24749	16065	10859	26710	17386	23226
27914	15481	29957	26687	25826	23132	20873	17733
26444	21906	25632	29753	25765	27058	19712	27475
16676	14106	19887	10624	26551	15285	23549	25877
23636	23015	14746	19548	28728	14822	14182	15449
25516	16628	22061	13680	11749	16178	14617	28183
28737	10637	21872	10876	18498	20431	26806	22500
15104	28093	25346	21253	27943	17361	16754	22377
11737	17509	13747	26210	24464	23493	28279	26419
20974	10310	11893	20295	29049	26861	28700	29468
17450	16418	25664	14244	29183	28604	17314	16898
23853	24332	26006	21873	11943	21190	10861	25152
23192	21989	14539	24274	24490	16884	10655	26872
25406	20192	24139	25823	16613	28273	21534	15758
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21818	17539	17876	18566	18460	14378	19935	10797
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10931	14641	27496	19202	10061	19298	26481	27437
16021	14720	26631	18755	20141	13709	13029	28136
29854	17801	26536	29081	27876	26820	23665	13435
14751	18685	10501	15372	29603	16253	21435	22233

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