Software Defined Pulse-Doppler Radar for Over-The-Air Applications:

The Joint Radar-Communications Experiment

by

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ABSTRACT

In this paper, the Software Defined Radio (SDR) platform is considered for building a pseudo-monostatic, 100MHz Pulse-Doppler radar. The SDR platform has many benefits for experimental communications systems as it offers relatively cheap, parametrically dynamic, off-the-shelf access to the Radiofrequency (RF) spectrum. For this application, the Universal Software Radio Peripheral (USRP) X310 hardware package is utilized with GNURadio for interfacing to the device and MATLAB for signal post-processing. Pulse doppler radar processing is used to ascertain the range and velocity of a target considered in simulation and in real, over-the-air (OTA) experiments. The USRP platform offers a scalable and dynamic hardware package that can, with relatively low overhead, be incorporated into other experimental systems. This radar system will be considered for implementation into existing over-the-air Joint Radar-Communications (JRC) spectrum sharing experiments. The JRC system considers a co-designed architecture in which a communications user and a radar user share the same spectral allocation. Where the two systems would traditionally consider one another a source of interference, the receiver is able to decode communications information and discern target information via pulse-doppler radar simultaneously.
This one is for Tiny Gina and for all of my friends who give me purpose.
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Two years ago when I tentatively strolled into Dr. Daniel Bliss’ office and asked him to consider me for a research position, he would have been well within his rights to laugh my unqualified and historically underperforming self out of there, but he gave me a shot instead. I would like to thank him now as profusely as is appropriate for the unwavering guidance and constant reassurance he has provided me in the face of all of my personal and professional challenges. I certainly would not have made it this far otherwise.

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>LIST OF TABLES</th>
<th>vi</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
</tbody>
</table>

## CHAPTER

1. **Introduction**
   - 1.1 Background .......................... 1
   - 1.2 Prior Works .......................... 2
   - 1.3 Motivation and Contributions .......... 4
2. **Pulse-Doppler Radar** .......................... 6
   - 2.1 System Model .......................... 6
   - 2.2 Pulse-Doppler Processing ............... 7
   - 2.3 The Radar Range Equation ............... 9
   - 2.4 The Ambiguity Function .................. 10
   - 2.5 Spectral Congestion and Spectrum Sharing with Radar ........... 11
     - 2.5.1 WISCAnet .......................... 14
3. **Pulse Doppler Radar Simulations** ................. 16
   - 3.1 Simulation for a Static Target .......... 16
   - 3.2 Simulation for a Mobile Target .......... 17
4. **Radar System Hardware Considerations** ........... 23
   - 4.1 Hardware Specification .................. 23
5. **Over-The-Air Experimentation** .................. 26
   - 5.1 Blanking the Transmit Pulse .............. 27
   - 5.2 Experimentation and Results .............. 29
     - 5.2.1 Further Results - Moving Target ....... 30
6. **The Joint Radar-Comms Experiment** ............... 33
<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Motivation</td>
<td>33</td>
</tr>
<tr>
<td>6.2 The Estimation Rate Metric and JRC</td>
<td>33</td>
</tr>
<tr>
<td>6.3 The JRC Experiment</td>
<td>34</td>
</tr>
<tr>
<td>6.4 The JRC System Model</td>
<td>35</td>
</tr>
<tr>
<td>6.5 The JRC Receiver</td>
<td>37</td>
</tr>
<tr>
<td>7 JRC Implementation of Over-the-Air Radar</td>
<td>41</td>
</tr>
<tr>
<td>7.1 Results</td>
<td>41</td>
</tr>
<tr>
<td>8 Conclusion</td>
<td>47</td>
</tr>
<tr>
<td>8.1 Future Work</td>
<td>47</td>
</tr>
<tr>
<td>8.2 Final Thoughts</td>
<td>47</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>49</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Radar Simulation Operating Parameters - Static Target</td>
</tr>
<tr>
<td>3.2</td>
<td>Radar Simulation Operating Parameters - Mobile Target</td>
</tr>
<tr>
<td>4.1</td>
<td>Radar System Hardware Parameters</td>
</tr>
<tr>
<td>6.1</td>
<td>Communications System Parameters</td>
</tr>
</tbody>
</table>
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Spectrogram of a Linear Frequency Modulated Chirp</td>
<td>7</td>
</tr>
<tr>
<td>2.2</td>
<td>Pulse-Doppler Processing Diagram</td>
<td>8</td>
</tr>
<tr>
<td>2.3</td>
<td>Radar Waveform Ambiguity Function</td>
<td>11</td>
</tr>
<tr>
<td>2.4</td>
<td>Zero-Doppler Cut - Ambiguity Function</td>
<td>12</td>
</tr>
<tr>
<td>2.5</td>
<td>Zero-Delay Cut - Ambiguity Function</td>
<td>13</td>
</tr>
<tr>
<td>2.6</td>
<td>WISCA SDR Network (WISCAnet) Operation Diagram</td>
<td>15</td>
</tr>
<tr>
<td>3.1</td>
<td>Pulse-Doppler Radar Ranging Simulation for a Static Target</td>
<td>18</td>
</tr>
<tr>
<td>3.2</td>
<td>Pulse-Doppler Radar Velocity Estimate Simulation for a Static Target</td>
<td>19</td>
</tr>
<tr>
<td>3.3</td>
<td>Pulse-Doppler Radar Ranging Simulation for a Mobile Target</td>
<td>21</td>
</tr>
<tr>
<td>3.4</td>
<td>Pulse-Doppler Radar Velocity Estimate Simulation for a Mobile Target</td>
<td>22</td>
</tr>
<tr>
<td>4.1</td>
<td>Photo of the OTA Radar System</td>
<td>25</td>
</tr>
<tr>
<td>5.1</td>
<td>Spectrogram of the LFM Chirp used in OTA Experiments</td>
<td>27</td>
</tr>
<tr>
<td>5.2</td>
<td>Trihedral Corner Reflector</td>
<td>28</td>
</tr>
<tr>
<td>5.3</td>
<td>Transmit Pulse Time-Domain Blanking and Suppression</td>
<td>29</td>
</tr>
<tr>
<td>5.4</td>
<td>Range-Doppler Matrix for Single CPI, Static Target</td>
<td>30</td>
</tr>
<tr>
<td>5.5</td>
<td>Range-Doppler Matrix for Single CPI, Moving Target</td>
<td>31</td>
</tr>
<tr>
<td>5.6</td>
<td>Estimated Range Over Time for Moving Target</td>
<td>32</td>
</tr>
<tr>
<td>6.1</td>
<td>Current Architecture of the JRC System</td>
<td>35</td>
</tr>
<tr>
<td>6.2</td>
<td>Proposed Architecture of the JRC System</td>
<td>36</td>
</tr>
<tr>
<td>6.3</td>
<td>Structure of the JRC Communications Waveform</td>
<td>37</td>
</tr>
<tr>
<td>6.4</td>
<td>Receive Architecture Block Diagram</td>
<td>39</td>
</tr>
<tr>
<td>6.5</td>
<td>Photo of the JRC Hardware</td>
<td>40</td>
</tr>
<tr>
<td>7.1</td>
<td>Over-The-Air Experiment Layout</td>
<td>41</td>
</tr>
<tr>
<td>7.2</td>
<td>SIC Approximation of Transmit Comms Waveform, 5 taps.</td>
<td>42</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>7.3</td>
<td>SIC Approximation of Transmit Comms Waveform, 19 taps.</td>
<td>43</td>
</tr>
<tr>
<td>7.4</td>
<td>Temporal Suppression of Communications Waveform - Post SIC</td>
<td>44</td>
</tr>
<tr>
<td>7.5</td>
<td>Range-Velocity Matrix of Composite Waveform, Pre SIC</td>
<td>45</td>
</tr>
<tr>
<td>7.6</td>
<td>Range-Velocity Matrix of Composite Waveform, Post SIC</td>
<td>46</td>
</tr>
</tbody>
</table>
Chapter 1

INTRODUCTION

1.1 Background

Software Defined Radio (SDR) is a radio and communication system platform rapidly increasing in its ease of use and capability to access the RF spectrum. The term SDR constitutes both the RF hardware package that allows for access to the RF spectrum as well as the enabling software (GNURadio) and firmware (USRP Hardware Driver). This hardware and software platform coupled with MATLAB signal processing provides a user a completely holistic over-the-air radio system, from sample generation to RF transmit and receive. This software/hardware paradigm, which has been used extensively in prototyping and characterizing of communications systems, will be considered for designing and constructing a 100MHz radar that uses Pulse-Doppler processing techniques to determine a target’s range and velocity. That radar system will then be considered for implementation in the Joint Radar-Communications experiment as presented by Gutierrez et al. (2019).

The goals this work achieves are two-fold; first a USRP based Pulse-Doppler radar is developed and secondly that radar system is implemented into an existing experimental JRC system. This chapter serves as an introduction. In Chapter 2, Pulse-Doppler radar processing is briefly discussed. A system model that will reflect the real over-the-air experimental conditions is presented. Additionally, the processing, algorithms, assumptions, and some enabling technologies are also considered. Chapter 3 offers a set of simulations to ensure that the Pulse-Doppler implementation operates as desired. First, a simulation involving a static target positioned approx-
imately 37 meters is simulated as this mirrors the setup of future experimentation. A slightly more interesting simulation involving a moving target is also presented to ensure the operation of the Pulse-Doppler processing chain. Chapter 4 specifies the hardware used for the over-the-air experiments. An overview of the hardware specified as a result of a link budget and the radar range equation introduced in Chapter 2 is given. The basis for the experimental system is the USRP X310, but peripheral hardware is required to enable the system. Chapter 5 presents and discusses the results of the aforementioned over-the-air experiments and verifies their efficacy. It serves to verify that the developed system can accurately range a static, trihedral reflector target. Chapter 6 introduces the concepts of the JRC experiment, including its motivation, model, and the foundational Successive Interference Cancelation (SIC) algorithm. The JRC setup is the motivator behind developing such an over-the-air USRP based Pulse-Doppler radar. The JRC receiver is detailed in depth. Chapter 7 finally presents the implementation of the JRC system with the OTA radar and shows the noise suppression capabilities of the SIC algorithm. A combination of new hardware and the setup demonstrated by Gutierrez et al. (2019) is shown to successfully extend the capability of prior experimentation. A conclusion is offered that explores further work that can be done on the topic.

1.2 Prior Works

The work in developing a USRP based radar system sets the foundation for much more experimental contribution than is included in this document. However, the development of such a system is non-trivial in its own right. There exists for GNURadio a radar toolbox that has been developed by Wunsch (2018) and others, which is generally preferred by the USRP user community. However there does not seem to be much published on the marriage of USRP, MATLAB, and pulse radars. Researchers
such as Kafedziski and Pecov (2017), Sundaresan and Zacharia (2015), and Mathumo et al. (2017) have used USRP SDRs to build frequency modulated continuous wave radar systems enabled by the GNURadio radar toolbox. Passive radar systems like the one demonstrated by Berizzi et al. (2010) are a favorite of the USRP community, both academic and hobbyist, and they are well represented in literature. Finally, Chinnam and Madhusudhan (2010) demonstrated the possibility to use software defined radio to implement a low cost synthetic aperture radar system. This all goes to show that the USRP platform can be leveraged to build a breadth of radar systems, but to date most have been based upon the toolbox developed by Wunsch (2018) and the open source community. There have been some military applications using SDRs for radar, but published contributions in the area of pulsed radar using SDRs is minimal.

Aside from the development of the actual radar, a more overarching concept that Joint Radar-Communications system seeks to address is spectral congestion. Griffiths et al. (2015) best describes the electromagnetic (EM) spectrum (1MHz-300Ghz) as a precious resource that many services society has come to rely on utilize, and demand for EM is only increasing. These services include communications, but also automotive safety, weather tracking, surveillance, and defense. He argues that radar is particularly fundamental to many of these services and that to ensure its continued unfettered operation, different regulations on use of the EM spectrum can be imposed or new technologies must be developed to better utilize the available spectrum in the face of a growing communications user base. Paul et al. (2017) explore the notion of co-designed communications and sensing (radar) systems that address this problem of spectral congestion for legacy radar users. The Joint Multiple Access Channel topology, one with a monostatic radar and a communications user with prior knowledge of each other, described by Paul et al. (2017) and earlier by Bliss (2014) is the one
considered for over-the-air experimentation in this paper.

Not much over-the-air experimentation has been done for co-designed systems such as the Joint Radar-Communications (JRC) system. The basis for this work is the experimentation done by Gutierrez et al. (2017, 2019), which shows experimentally the viability of such a system and explores its performance based on work done by Bliss (2014). The goal achieved by that work was to characterize the performance of the system based on its communication and estimation rates.

1.3 Motivation and Contributions

The motivation for the work herein is to both build and demonstrate the operation of a Pulse-Doppler radar system using the USRP platform and subsequently demonstrate its operation in the context of the Joint Radar-Communications experiment conducted by Gutierrez et al. (2019). In that work, the joint sensing and communications system performance is characterized in terms of the communication and estimation rates based on a receiver sensing a communications waveform and an estimated radar return. Prior criticisms of that work suggest that because not a true radar return, but rather an estimate of a radar return (see Figure 6.1), is used, the system does not do enough to properly characterize the true phenomenon. This paper intends to assuage those concerns by working towards implementing a true radar return into the receive processing chain. This work achieves the following:

1. Presents an overview of Pulse-Doppler radar and specifies the hardware necessary to implement such a system using a USRP X310 and peripheral hardware.

2. Implements a Pulse-Doppler radar based on SDR and presents the results of over-the-air experimentation tracking a static target.

3. Installs the aforementioned radar system into the Joint Radar-Communications
experiment as designed and tested by Gutierrez et al. (2019).

4. Demonstrates the operation of the modified JRC system and shows the noise suppression capabilities of the receive processing chain.

While this work does not go so far as to completely mimic the work done in the initial JRC experiments, it serves as a proof of concept that the system can in fact be extended to include a true radar return. Mitigating spectral congestion using co-designed communications systems presents a solution to an ever looming problem. The field is rich for further study, and the culmination work described throughout this paper represents a novel contribution to what could be an avenue for all kinds of future work.
Chapter 2

PULSE-DOPPLER RADAR

Pulse-Doppler Radar is a radar technique that uses the time-of-arrival of a reflected pulse to estimate the range of a target and the Doppler frequency shift of the target to estimate its radial velocity. The parameters of the system can be tuned to the environment in which it must operate and the types of targets it is trying to estimate. This parameter specification is paramount in developing an efficacious radar system.

2.1 System Model

For the simulations done, the Swerling V model is assumed for the target. That is, the target has a constant radar cross-section across pulses and processing intervals as shown in Richards (2014). This is an adequate approximation as the target in question does not change in size or orientation over the course of the experiment. A linear frequency modulated (LFM) pulse called $s(t)$ is transmitted via the radar transmitter through an additive white Gaussian noise (AWGN) channel. The radar return, $z(t)$, is a complex-scaled, time-delayed copy of the sent pulse with added noise described as

$$z(t) = bs(t - \tau) + n(t) = ae^{i\phi}s(t - \tau) + n(t)$$

(2.1)

where $a$ is the attenuation of the signal, $\phi$ is the phase offset caused by the Doppler shift, and $\tau$ is the time delay of the reflection. A visualization of the waveform $s(t)$ can be seen in Figure 2.1

6
Figure 2.1: The spectrogram of the LFM chirp describes the waveform in both frequency and time. The chirp used in the simulations sweeps across 100MHz over the course of 1.5 $\mu$s. The bandwidth of the waveform dictates the range resolution of the system and the pulse width dictates the minimum range at which the system can detect a target. These are two major considerations of the experimental system.

2.2 Pulse-Doppler Processing

The range of the target from the transmit antenna is simply the velocity of the waveform multiplied by the amount of time traveled

$$R = \frac{c}{2} \tau$$  \hspace{1cm} (2.2)

where $c$ is the speed of light. The factor of 2 is introduced because the pulse covers the distance to the target twice: once on the path towards the scatterer, and once more on the return path.

The velocity of the target can be estimated by
\[ f_D = \frac{1}{2\pi} \frac{d(\phi)}{dt} = \frac{2v_r f_C}{c} = \frac{2v_r}{\lambda} \tag{2.3} \]

where \( f_D \) is the doppler frequency, \( f_C \) is the carrier frequency of the radar system, \( v_r \) is the radial velocity of the target, and \( \lambda \) is the wavelength of the transmitted signal. Subsequently, the velocity can be obtained easily as:

\[ v_r = \frac{\lambda f_D}{2} \tag{2.4} \]

**Figure 2.2:** Shown is a simplified diagram of the Pulse-Doppler Processing chain. A matched filter is used along pulses and an FFT is taken across them. Moving along the Y-axis is called ”fast-time” because each bin corresponds to one sample at the the radar sample frequency. Moving along the X-axis is called ”slow-time” because each bin corresponds to the one sample at the pulse-repetition frequency, which is typically on the order of \( 10^3 \) or more times slower the frequency of fast-time. If a target is present and detected, the bin with the most energy corresponds to the range and velocity of the target.

As shown in Figure 2.2, a matched filter is used along each pulse to find the reflected energy in each range bin. The space along the pulses is called ”fast-time”, and each bin corresponds to the period of one sample, \( T_s \) or \( \frac{1}{f_s} \), of the radar system. The bin containing the most energy corresponds with the estimated range of the target, assuming it passes the detection threshold. Then, an FFT is taken across the
pulses to give the doppler frequency shift between pulses. Each doppler frequency corresponds to a radial velocity that is a function of the wavelength of the system carrier frequency. Accordingly, this "slow-time" can then be directly translated to an estimate of the radial velocity of the target as per Richards (2014) and many other sources. It is called slow-time because each subsequent bin corresponds in time to $\frac{1}{PRF}$, the time it takes to send a pulse. The methods described make up the bulk of the processing done in MATLAB for both the simulations and the OTA experiments.

2.3 The Radar Range Equation

Whether or not the radar system will be operable under given conditions can be determined by the radar range equation. This relationship dictates the amount of power necessary at the transmitter to resolve a target of a given cross section at a given range. A minimum Signal to Noise Ratio (SNR) for system operation can be estimated using Albersheim’s equation as per Richards (2014). The equation yields a minimum SNR required for a certain level of system performance. The system performance is characterized by the probability of detection ($P_D$) and the probability of false alarm ($P_{FA}$). The user specifies the desired probabilities and the estimation tells the user the SNR required to achieve said probabilities. Albersheim’s equation is given as:

$$SNR = -5logN + \left[6.2 + \frac{4.54}{\sqrt{N + 0.44}}\right]log(A + 0.12B + 1.7B)$$ (2.5)

where

$$A = ln\left(\frac{0.62}{P_{FA}}\right),$$ (2.6)

$$B = ln\left(\frac{P_{D}}{1 - P_{D}}\right)$$ (2.7)

Once a minimum SNR is estimated, the radar range equation can be used to
estimate the necessary power at the radar transmitter using

\[ P_{\text{min}_{tx}} = \frac{(4\pi)^3 F_n k T_s R_t^2 R_r^2 (SNR)}{\tau G_t G_r \sigma \lambda^2 L} \]  

(2.8)

where \( P_{\text{min}_{tx}} \) is the minimum amount of power required at the transmitter to detect a target of radar cross section \( \sigma \) at range where \( R_t \) is the transmit range and \( R_r \) is the return path range. For this system, which uses two separate but closely located antennas for transmit and receive, the transmit path and the return path will be of nearly identical length. This approximates the operation of a monostatic radar. A monostatic radar is one that uses the same antenna to transmit and receive and as such the transmit and return path are nearly identical. The alternative, a bistatic radar, uses two separate antennas that are typically located far enough away from one another that the transmit and return paths are of significantly different lengths. The experimental system described later is bistatic in that separate antennas perform the transmit and receive functions, but it closer approximates the operation of a monostatic system because they are so close.

2.4 The Ambiguity Function

The Ambiguity function is, per Richards (2014), is the most succinct way to analyze a radar waveform. It describes the output of the matched filter used to acquire the signal for different range and doppler mismatches. The function allows a brief way to analyze the ambiguities in range and doppler for a given radar waveform as well as the sidelobe levels and is defined by:

\[ A(t, F_D) = \int_{-\infty}^{\infty} x(s) \exp(j2\pi F_D s)x^*(s - t)s \]

(2.9)

where \( t \) and \( F_D \) define the time delay and doppler spread and \( x(s) \) is the waveform of interest. For a system in which \( x(s) \) is a Linear Frequency Modulated (LFM) chirp,
the ambiguity function becomes:

\[
|A(t; F_D)|^2 = \left| \left( 1 - \frac{|t|}{t'} \right) \sin \left( \frac{\pi t' (\mu t + F_D)}{\pi t' (\mu t + F_D)} \left( 1 - \frac{|n|}{t'} \right) \right) \right|^2
\]

(2.10)

Figure 2.3: The ambiguity function is a straightforward way to analyze the characteristics of a radar waveform. This curve is typical of any LFM waveform.

For a waveform with the parameters that will be used in later sections (see 3.1), the ambiguity function can be evaluated for zero Doppler and zero Delay.

2.5 Spectral Congestion and Spectrum Sharing with Radar

One of the motivations for implementing a radar using the USRP platform is to extend the work done by Gutierrez et al. (2017, 2019). Gutierrez et al. (2017, 2019) designed and tested a joint sensing and communications experiment in order to
evaluate the performance bounds of such a spectrum sharing system. Essentially, a communications signal carrying arbitrary data and a radar waveform are transmitted over-the-air, in-band, simultaneously. At the receiver, multiple signal processing algorithms and techniques are employed to disentangle the two waveforms such that the data sent by the communications system can be recovered and that range and velocity information can be ascertained from the radar return waveform. Such a co-designed system could become paramount to mitigating the effects of RF spectral congestion.

RF spectral congestion has arisen from an increase in demand of communications users that saturate available frequency bands. There are various ways to address this
Figure 2.5: The Zero-Delay cut of a LFM chirp waveform. This shows the Doppler mismatch when there is no mismatch in the delay.

problem, namely system co-existence or system co-design. The work by Chiriyath et al. (2017) and the aforementioned authors is system co-design. That is to say, both the radar and the communications system are designed with the other in mind, and information from each is used to decode the other at the receiver. Where typically a radar user and a communications user would be competing for spectrum and would view one another as interferers, in a co-designed system this is not the case. The information from each waveform can actually be used cooperatively to increase the performance of the other, as per Bliss (2014).

In the experiment by Gutierrez et al. (2017, 2019), the radar return that is processed at the receiver is not a true reflection off of a target. Instead, a radar return
is estimated based on a target simulated in MATLAB and this simulated radar return waveform is transmitted directly from one radio to the receiver. That is to say, in the experiment there is no target and no radar transmitter, but rather a radio that transmits an approximation of what a radar return would look like at the receiver. This experiment runs on a system nominally referred to as WISCAnet as designed by Yu et al. (2017).

2.5.1 WISCAnet

WISCAnet enables the experiment by networking multiple computers (edge nodes), each with a dedicated USRP device for transmit and receive, and controlling them via a single computer deemed the control node. The software utilizes UDP Networking, GNURadio, the USRP Hardware Driver (UHD), and MATLAB to do networking, over-the-air transmission and reception, and data processing. Spreading the computational resources over multiple devices reduces the bottleneck of having to process too much data on a single machine and allows for scalable, dynamic systems. The operation of the WISCAnet itself toggles between transmit/receive sequences and data processing sequences, each on the order of seconds, in order to approximate a real time system.

The implementation of a radar system using the same USRP platform than enables WISCAnet will allow for the experiment to be extended to using a true radar return as opposed to a simulated one, constituting a novel contribution to the field of study.
Figure 2.6: The WISCA SDR Network simulates a real time communications system by cycling between transmit/receive and processing blocks. The USRP radar system can be seamlessly integrated into the existing system. (Image courtesy Hanguang Yu)
Chapter 3

PULSE DOPPLER RADAR SIMULATIONS

The MATLAB programming environment is used to develop a simulation of a target whose range and velocity could be estimated using Pulse-Doppler processing. The over-the-air experiment will occur inside in a lab setting, so radar parameters are chosen with these environmental constraints in mind. For the over-the-air experiment, the target will be an aluminum trihedral reflector positioned approximately 37m from the radar, and it will not be moving.

3.1 Simulation for a Static Target

A simulation for a static target is conducted in MATLAB for the purposes of verifying the Pulse-Doppler processing algorithms and ensuring that the system is feasible and realizable.

The simulation is run using the parameters that are expected to be used in the over-the-air experiment as shown in Table 3.1. Some results are shown in Figures 3.1 and 3.2.

The results of the simulation suggest that there is some intrinsic error in the processing due to the parameters that determine the range and velocity resolution. Both the range and velocity estimates are slightly off, but the error does not fluctuate. One could assume that the processing works reasonable well after this simulation, but a slightly more complicated simulation can also be designed to verify this even though the tools to replicate it over-the-air are not available.
### Radar Simulation Operating Parameters - Static Target

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<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>CPI - Coherent processing interval</td>
<td>32</td>
</tr>
<tr>
<td>$F_c$ - Carrier frequency</td>
<td>5.8 GHz</td>
</tr>
<tr>
<td>$\lambda$ - Wavelength</td>
<td>0.0517 m</td>
</tr>
<tr>
<td>B - Bandwidth</td>
<td>100 MHz</td>
</tr>
<tr>
<td>PWP - Pulse width percentage</td>
<td>0.06%</td>
</tr>
<tr>
<td>$\tau$ - Pulse Duration</td>
<td>2e-7 s</td>
</tr>
<tr>
<td>$R_t$, $R_r$ - Target Range</td>
<td>37 m</td>
</tr>
<tr>
<td>$v_r$ - Target velocity</td>
<td>0 m/s</td>
</tr>
<tr>
<td>$\sigma$ - Target Cross Section</td>
<td>$\sim$500m$^2$</td>
</tr>
<tr>
<td>Range resolution</td>
<td>1.5m</td>
</tr>
<tr>
<td>Unambiguous range</td>
<td>4996.5 m</td>
</tr>
<tr>
<td>Unambiguous velocity</td>
<td>387.66 m/s</td>
</tr>
</tbody>
</table>

**Table 3.1:** Table showing the operating parameters for the radar system simulated in MATLAB for a static target.

### 3.2 Simulation for a Mobile Target

A more interesting simulation is provided to better show the performance of the Pulse-Doppler processing chain with updated parameters as shown in Table 3.2.

The updated simulation, while still simple, will offer some better insight as to the performance of the Pulse-Doppler processing. The target model is essentially a large target that starts at a position 3500m from the radar that begins accelerating at a constant rate of 1m/s radially towards the radar. This will test the system's ability to estimate the velocity of a target as well as its accuracy across range bins.
Figure 3.1: Pulse Doppler radar ranging simulation results for static, 30m target.

The results of the Pulse-Doppler processing track well with the simulated target and are a convincing argument that the processing chain works as intended. Note that as the CPI is increased, the estimate of the target velocity converges with the true velocity of the target. It is determined, however, that due to the constraints of the physical system a CPI of 64 is adequate.

The simulations shown above should be convincing that the Pulse-Doppler processing chain developed in MATLAB performs as expected and can be utilized in an over-the-air experiment on real-world data.
Figure 3.2: Pulse Doppler radar velocity estimate simulation results for static, 30m target.
<table>
<thead>
<tr>
<th>Radar Simulation Operating Parameters - Mobile Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPI - Coherent processing interval</td>
</tr>
<tr>
<td>PRF - Pulse repetition frequency</td>
</tr>
<tr>
<td>$F_c$ - Carrier frequency</td>
</tr>
<tr>
<td>$\lambda$ - Wavelength</td>
</tr>
<tr>
<td>B - Bandwidth</td>
</tr>
<tr>
<td>PWP - Pulse width percentage</td>
</tr>
<tr>
<td>$\tau$ - Pulse Duration</td>
</tr>
<tr>
<td>$R_t$, $R_r$ - Target Range</td>
</tr>
<tr>
<td>$v_t$ - Target velocity</td>
</tr>
<tr>
<td>$\sigma$ - Target Cross Section</td>
</tr>
<tr>
<td>Range resolution</td>
</tr>
<tr>
<td>Unambiguous range</td>
</tr>
<tr>
<td>Unambiguous velocity</td>
</tr>
</tbody>
</table>

**Table 3.2:** Table showing the operating parameters for the radar system simulated in MATLAB for a mobile target.
Figure 3.3: Pulse Doppler radar ranging simulation results for mobile target. The ranging capability of the processing performs well. MSE = 0.6778
Figure 3.4: Pulse Doppler radar velocity estimate simulation results for mobile target. The velocity estimating capability of the processing performs adequately. Better performance can be achieved by increasing the CPI. MSE = 5.6460
In order to build the actual radar system, hardware and equipment must be specified to meet the requirements as calculated using the radar range equations introduced previously.

4.1 Hardware Specification

By the nature of software defined radio, the operating parameters can be tuned easily and "on the fly" as necessary. The USRP X310 and UBX-160 frontend run on the AD9361 chipset and have a full 200MHz bandwidth available, but the PC running the device can only handle about half of that bandwidth when doing a simultaneous

<table>
<thead>
<tr>
<th>Radar System Hardware Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
</tr>
<tr>
<td>Amplifier</td>
</tr>
<tr>
<td>SDR</td>
</tr>
<tr>
<td>Frontend</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Antenna Directional Gain</td>
</tr>
<tr>
<td>Amplifier Gain</td>
</tr>
<tr>
<td>Frontend transmit power</td>
</tr>
<tr>
<td>Noise Figure (RX) ($F_{n}$)</td>
</tr>
<tr>
<td>Atmosphere loss coefficient</td>
</tr>
</tbody>
</table>

Table 4.1: Table showing the operating parameters for the hardware specified for the radar system.
transmit and receive. Anything higher and the user risks underflow and overflow errors on the transmit and receive buffers. Underflow errors cause the transmitter to drop samples and introduce high frequency spikes in the transmit waveform. The system can still operate under these conditions, but the receive processing becomes slightly more complicated. Overflow errors on the receiver tend to break the system, however, as samples are dropped and time-domain information about the receive waveform becomes ambiguous. Even at 100MHz, underflow errors occur only on start-up at the transmitter but cease once everything settles to steady-state. This just means that a comparatively small amount of data during the first few transmit cycles must be thrown out.

A link budget was conducted using the radar ranging equation to ensure that the system meets the requirements to detect a return based on information in Richards (2014). An estimate of the SNR required at the receiver to achieve a probability of detection $P_d = 0.99$ and a probability of false alarm $P_{fa} = 1e - 12$ was calculated using Albersheim’s Equation and yielded an SNR of 5.8dB per Richards (2014).

$$SNR = -5logN + \left[6.2 + \frac{4.54}{\sqrt{N} + 0.44}\right]log(A + 0.12B + 1.7B)$$

$$SNR \approx 5.8dB$$

Using the radar range equation from earlier, a link budget can be calculated with the given parameters acquired from hardware datasheets and the previously calculated required SNR. After evaluation, $P_{minx}$ comes out to something like -7dbm due to the short range and relatively large target. This power is easily achieved by the front-end of the USRP without the help of an external amplifier. Because the power required goes like $\frac{1}{R^2}$, the necessary power at the transmitter increases significantly as the
Figure 4.1: A photograph of the USRP X310 and horn antenna rig that constitutes the majority of the hardware for the system. The device approximates a monostatic radar because the antennas are so close together and the receiver gets blanked during transmit in post processing.

As such, an externally powered amplifier shall be used for future use of the system.

\[
P_{\min_{tx}} = \frac{(4\pi)^3 F_n k T_r R_t^2 R_r^2 (SNR)}{\tau G_t G_r \sigma \lambda^2 L} \approx -7 \text{dbm} \quad (4.1)
\]
The experiment to test the operation of the USRP based radar system was designed in part with the lab environment in mind. The experiment took place in a long, narrow hallway in a research facility. The radar system as shown in Fig. 4.1 was placed at one end of the hallway, and the trihedral reflector acting as the target was placed approximately 37 meters downrange at the other end of the hallway. The experiment was conducted in the 5.8GHz ISM band, which is also actively used for WiFi communications. There was noticeable interference from WiFi users in the building, but it did not seem to significantly effect the performance or outcome of the experiment.

Note that as shown in Figure 5.1, the chirp has to be shortened in time to accommodate for the limited amount of space available in the lab environment. For a system in which there is a desired minimum range, the maximum pulse width in seconds,

\[
\tau = \frac{2R_{\text{min}}}{c}
\]

where \(c\) is the speed of light. For a target only approximately 30 meters away, solving for the width of the radar pulse yields an absolute maximum \(\tau\) of only 200 nanoseconds. At a sample rate of \(f_s = 100\text{MHz}\) or alternatively period \(T_s = 10\text{ns}\), only 20 samples can be allocated to the radar pulse in order to not eclipse the closely positioned target. Ideally, the pulse width would be longer, but it turns out that this
Figure 5.1: The spectrogram of the chirp waveform, perhaps more of a *peep* than a chirp, used in the over-the-air experiment had to be shortened in time to accommodate for the range of the target. It is not well defined in frequency, but performs well for the application.

outcome is workable for the purposes of this experiment.

5.1 Blanking the Transmit Pulse

The operation of the proposed radar system is bistatic in that there are two separate antennas for each the transmit and receive chains of the system, and the receiver is always listening while the system is on. Due to this, the receiver sees both the reflection off of the target and any other scatterers in the environment as well as from the initial burst from the transmitter. In order to properly process the receive data, the receiver has to be able to distinguish between the initial burst and any reflections. An algorithm to time align the transmit and receive waveforms and
Figure 5.2: The trihedral corner reflector used as a target for the over-the-air experiments.

then do temporal blanking of the initial transmit is employed, and in this manner the system actually approximates the operation of a monostatic radar. It is relatively easy to discern the transmit pulse from any reflections because the amplitude of the
initial pulse is necessarily the highest, and it occurs at a regular frequency. Tuned properly, the algorithm can be sure that it is only blanking the transmit pulse.

![Time-Domain Receive Waveform, Pre-Blanking](image1)

![Time-Domain Receive Waveform, Post-Blanking](image2)

**Figure 5.3:** Demonstration of the effect of the transmit pulse blanking procedure. The receiver uses a matched filter to determine the location of a pulse and ensures that its index is consistent with past and future pulses. It then blanks (sets the value to zero) the time duration of the pulse, allowing for Pulse-Doppler processing to occur only on the reflections.

5.2 Experimentation and Results

For the experiment, multiple waveforms of differing pulse widths and amplitudes were tested to varying results. They include the aforementioned LFM chirp, a shortened in time LFM chirp used in order to reduce the minimum range of the system, and a short tophat pulse that was intended to discern whether or not there was any return energy at the receiver. The longer in time LFM chirp turned out to be too wide such that that the transmit pulse would still be on when the wavefront of the
return arrived. The tophat worked as intended and did confirm that energy was being returned from the reflector target. The waveform that performed the best was the condensed in time LFM chirp, and that is the waveform used in the run whose data is presented here.

![Normalized Range-Velocity Matrix over Single Coherent Processing Interval](image)

**Figure 5.4:** Range-Doppler matrix for a single CPI for the radar system. The axis have been translated to absolute range and velocity as opposed to range bin and doppler. Nothing in the scene is moving and correspondingly, there is no energy outside of the doppler zero bin. Likewise, the highest energy is seen at the bin corresponding to approximately 34 meters. By inspection, it was determined that because of significant clutter in the scene, the target cannot be discerned.

Because there is so much clutter in the environment, a static target cannot be acquired. Reflections from scatterers in the environment mask any return seen from the target.

### 5.2.1 Further Results - Moving Target

Upon basic assessment of the performance of the experimental system for the static target, a test to garner a cursory understanding of the performance for a moving
target was conducted. In this experiment, the target is pulled away from the radar at an unmeasured but arbitrarily slow speed. The actual movement of the target is not explicitly characterized; the dataset serves only to validate that the receive processing operates as expected.

**Figure 5.5:** Range-Doppler matrix for a single CPI for the radar system for a slowly moving target. There is energy in negative doppler bins which corresponds to a target moving away from the antenna. This agrees with the expected result. This serves to provide evidence that the radar system does work as intended. Energy from the moving target can be discerned independent of all of the clutter in the environment.

Indeed the above Figures 5.5 and 5.6 show that there is energy in a doppler bin that corresponds to a target moving away from the radar and that the ranging also agrees that the target is moving away. This suggests that the Pulse-Doppler processing works as expected.
Figure 5.6: The range of the target moving slowly away from the radar over multiple CPIs is shown. The results of the processing and sinc interpolation suggest that the target is in fact moving backwards relative the radar. This is consistent with what is expected. For reference, the graphic suggests that the target is moving at approximately 0.9 meters per second.
THE JOINT RADAR-COMMS EXPERIMENT

The implementation of the USRP radar system demonstrated was motivated by the JRC experiment explored by Gutierrez et al. (2017, 2019). Because the explicit intent is to integrate this system into that that experiment, the concepts of the Joint Radar-Communications spectrum sharing will be explored further in this section.

6.1 Motivation

A co-designed, multiple-access spectrum sharing system is presented to address the problem of spectral congestion. The problem of spectral congestion can be attributed to an increase in the number of users for both radar and communications. The mutual cooperation of a communication and radar user is one proposed solutions in academia.

6.2 The Estimation Rate Metric and JRC

In order to adequately characterize a joint radar-communications (JRC) receiver, an information theoretic metric analogous to communications rate must be introduced. Bliss (2014) presents a novel metric called the estimation rate that allows for receiver performance bounds for a JRC system to be developed. The estimation rate is derived using information theoretic concepts and a bound for the metric is introduced. The metric is useful in that its units are in bits per second such that it matches the units of the communications rate, allowing for a convincing relationship between the two to be developed. From Bliss (2014), the approximate bound on the estimation rate $R_{est}$ is given by:
\[ R_{est} \leq B \log_2 \left( 1 + \frac{\sigma_{\tau,proc}^2 \gamma^2 B(TB)a_m^2 P_{radar}}{k_B T_{temp}} \right) \] (6.1)

where \( \gamma \) is the radar spectral shape parameter. This quantity by inspection can be interpreted as having units of bits per second. This bound can be used in conjunction with the communications rate given by the Shannon limit to characterize the performance of a JRC system:

\[ R_{comms} \leq B \log_2 \left( 1 + \frac{b^2 P_{comms}}{k_B T_{temp} B} \right) \] (6.2)

6.3 The JRC Experiment

Gutierrez et al. (2019) designed and implemented an OTA-JRC system to demonstrate the viability and performance of the proposed system architecture. The experimental system uses USRP B210 software defined radios to access the 915MHz industrial, scientific, and medical (ISM) band. It employs Pulse-Doppler processing of a linear frequency modulated (LFM) chirp waveform on the radar system and an encoded QPSK waveform on the communications system. The communications system has full functionality and can operate over the air not in the presence of interference and at 15dB SNR with zero bit error rate. The radar system, however, is not a truly implemented radar. Instead of illuminating a target with a chirp and processing the return, a clever data processing chain has been implemented at the radar transmitter to simulate what the return from a theoretical target traveling at a given range with a given velocity would look like. This simulated return is transmitted directly from the antenna of the USRP and processed at the receiver. This method works and is appropriate because the receiver cannot tell the difference between this simulated return and an actual radar return off of an illuminated target. While the system is fully functional in its current iteration, adding a legitimate reflected radar
### Communications System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>20MHz</td>
</tr>
<tr>
<td>Modulation</td>
<td>Turboencoded QPSK</td>
</tr>
<tr>
<td>Spread Factor</td>
<td>4</td>
</tr>
<tr>
<td>Total Message Bits</td>
<td>15,000</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>5.8Ghz</td>
</tr>
</tbody>
</table>

**Table 6.1:** Table showing the operating parameters for the communications side of the Joint system.

...return into the receive processing chain would represent a novel contribution.

![Simulated Radar Return Transmitter](image)

**Figure 6.1:** Current architecture of the JRC experimental system. A communications transmitter simulates what a radar return would look like at the receiver.

### 6.4 The JRC System Model

To model what is seen at the JRC receiver, \( z \), we consider a composite waveform composed of both the communications \( x_{\text{com}} \) and radar \( x_{\text{rad}} \) waveforms. The communications waveform consists of encoded, interleaved, and spread QPSK symbols. The radar pulse is a LFM chirp, much like the one used in simulation and over-the-air in previous chapters.
Figure 6.2: Proposed architecture of the JRC experimental system, with an operating OTA radar and an actual scattering target.

The signal seen at the receiver is given by

\[ z = z_{\text{com}} + z_{\text{rad}} \]  \hspace{1cm} (6.3)

\[ z = \sqrt{P_{\text{com}}x_{\text{com}}} * a + \sqrt{P_{\text{rad}}x_{\text{rad}}} * b + n \]  \hspace{1cm} (6.4)

where \( a \) and \( b \) are the complex channel attenuation coefficients and \( n \) is vector of additive complex Gaussian noise terms. The convolution operator is denoted with the * symbol and **bold** terms are row vectors as described by Gutierrez *et al.* (2017). The communications signal is an RRC pulse-shaped waveform of QPSK modulated symbols. Before the modulation, the data is encoded and interleaved with a forward error-correcting (FEC) code and then has a spreading sequence applied to it. The encoding and spreading makes the communications signal robust to noise introduced during transmission and during receive processing. The signal has to be decoded at
a low bit error rate in order to accurately separate the composite waveform $z$ into its component parts.

![Diagram of communications waveform structure](image)

**Figure 6.3:** Structure of the communications waveform, $x_c$, known to the receiver.

### 6.5 The JRC Receiver

The receiver of the proposed JRC system is implemented in roughly five stages:

1. First, the composite waveform is acquired and a coarse time and frequency alignment is achieved. Because this is a co-design system, the receiver has prior knowledge of both the radar and communications waveform. The receiver can create an estimate of what the radar return will look like based on how the transmit waveform was constructed. This radar estimate waveform is then subtracted from the composite received waveform in order to approximate just the received communications waveform. Because this version of the JRC system will be utilizing the over-the-air version of the Pulse-Doppler radar, consideration for the initial pulse must also be taken. The initial pulse cannot be blanked because there is potential for communications information being lost in that process, so a similar process can be used for both the initial radar transmit and the return to reject the radar interference in the communications processing.

2. The second step involves de-spreading, demodulating the symbols of the communications waveform in a manner reciprocal to how the original signal was created. This is essentially the normal receive processing chain for a communi-
3. Thirdly, because robust error correction is used in the design of the communications waveform, an accurate estimate of the raw data bits can be constructed. In this step, a channel model is also estimated.

4. In the fourth step, at the receiver, these bits are then re-encoded and modulated identically to how they would have been at the transmitter. This yields an approximate for the transmitted waveform, $\hat{x}_c$. This reconstructed waveform is then applied to the channel model to yield an approximate for the received communications waveform independent of the radar waveform.

5. In the fifth and final processing step, culminating the Successive Interference Cancellation (SIC) algorithm (described in greater detail by Gutierrez et al. (2017)) can be employed to obtain a high resolution estimate for the radar return. This is somewhat analogous to step one in which an estimate of the radar return is used to isolate the communications waveform. In the final step, the estimate of the communications waveform seen at the receiver is used to suppress the communications component of the composite, received waveform. This yields an isolated copy of only the radar waveform, as well as the communications waveform as estimated previously. This isolated radar waveform can then be analyzed using the Pulse-Doppler methods as discussed in earlier sections.

The entire receive process is predicated on being able to accurately estimate and suppress each waveform. On the radar side, this means successfully predicting the return. Typically, some filter or estimator would be updated after each CPI to predict the next return as in Gutierrez et al. (2019). Because this particular experiment uses
Figure 6.4: A block diagram shows the co-design architecture of the receiver. The receiver has prior information on both the communications waveform and the radar pulse. This information can be leveraged to isolate each component from the composite received waveform.

A static target, this is unnecessary. On the communications side, an accurate channel model and phase offset must be calculated in order to accurately reconstruct an estimate of the transmit waveform. The following chapter focuses on this aspect of the algorithm and increasing radar performance by suppressing the communications waveform.
Figure 6.5: A photo of the nominal WISCAnet, a bank of multiple USRP B210 radios and intelNUC computing units all networked together. One of these B210 radios will be used to transmit the communications waveform in Chapter 7.
The Joint Radar-Communications trials were run under the same conditions as the previous test of the Pulse-Doppler radar. They were done in a long hallway with a static target positioned 37 meters from the radar transmitter. Additionally, a USRP B210 is used to transmit the communications waveform described in figure 6.3. The waveform is centered at 5.8GHz and occupies 20MHz of bandwidth and is positioned adjacent to the radar transmitter and joint receiver.

\textbf{Figure 7.1:} A cursory graphic of the layout of the actual experiment is shown above. The trihedral reflector target is placed at the end of a long hallway with the radar and joint receiver at the other end. A communications signal is broadcast from inside an adjacent laboratory space from the bank of SDRs shown in 7.1

\section*{7.1 Results}

Because the communications waveform is so robustly coded and the radar waveform is relatively narrow in time (due to environmental constraints), the decoding of the waveform is relatively trivial. The communications rate achieved in these exper-
iments is about 2Mb/s. Gutierrez et al. (2019) used a synthetic radar return in their experiment to mimic the return of an actual target moving along some predetermined track. Because of that added complexity, a predictive Kalman filter was implemented in order to predict future returns to suppress the radar from the composite waveform, as described in Chapter 6. Since the target in this experiment is static, predicting the return is trivial and the added complexity of tracking is left out. Once the communications waveform is successfully extracted from the composite, an estimate of the transmitted waveform through the channel can be constructed.

![Rx Signal Estimate - Real, 5 Taps](image1)

![Rx Signal Estimate - Imag, 5 Taps](image2)

**Figure 7.2:** One component of the SIC algorithm is using a channel estimate to reconstruct an estimate of the transmitted communications waveform. A least squares estimate using 5 taps struggles to do this accurately.

A least squares estimator (LSE) is used to discern coefficients for the channel. Prior iterations of the experiment used five channel taps in order to do this, but the
performance was not sufficient in this case. Instead it was determined that a LSE using 19 taps offers a much better performance when reconstructing an estimate of the transmit waveform. A phase offset from the received communications signal must also be calculated, but constant phase offset across the message can be assumed. Figures 7.2 and 7.3 show how well the transmit waveform is constructed using a different number of taps in the LSE channel estimator. The blue trace shows the actual received and isolated communications waveform. The red trace shows the estimate created by reconstructing the transmit waveform and applying the measured phase offset and channel estimate to it.

![Rx Signal Estimate - Real, 19 Taps](image)

![Rx Signal Estimate - Imag, 19 Taps](image)

**Figure 7.3:** The least squares estimator using more taps performs markedly better. This estimate of the communications waveform allows for greater temporal suppression of the comms waveform from the composite received waveform.

Once the estimate of the transmit waveform is constructed, it can be time aligned
with the receive composite waveform and simply subtracted from it. The effect of this temporal suppression is shown in 7.4. Because the estimate of the transmit waveform is so accurate, the communications component of the composite waveform is almost entirely suppressed.

**Figure 7.4:** The composite waveform in blue, when being processed as a radar return, sees the overlaid communications waveform as interference. The SIC algorithm uses the estimated communications waveform shown above to suppress the actual communications waveform component of the composite. The result (red) in time shows a greatly reduced (∼6dB) noise floor.

Once the radar waveform is isolated from the composite after SIC processing, it can be analyzed using the previously developed Pulse-Doppler processing. Sure enough, as shown in the range-velocity matrix, the familiar static target positioned 37 meters from the radar transmitter surfaces. To illustrate the effect of the SIC processing, the composite waveform without additionally processing is also analyzed.
Figure 7.5: The composite waveform can undergo Pulse-Doppler processing to yield a range-velocity matrix. There is significant noise seen as a result of the in-band communications waveform.

As shown in figure 7.5, there is significant noise added by the in-band communications occurring simultaneously with the radar system. When not co-designed, the radar sees the communications signal only as interference.

Once the composite waveform undergoes SIC and then Pulse-Doppler processing, the result is significantly cleaner. In this example, the SIC processing reduces the noise floor created by the communications waveform about 6dB. There is still some noticeable interference, but its effects are greatly reduced as a result of the SIC receive processing chain.
Figure 7.6: The composite waveform has the Successive Interference Cancellation algorithm applied to it before Pulse-Doppler. There is a noticeable suppression of the noise introduced by the communications signal.
Software defined radio offers many avenues for the experimental testing and characterization of novel communications systems as the platform becomes more accessible, user-friendly, cheap, and deployable. Using the USRP as a basis for the design of a monostatic radar is no exception. Subsequently installing this radar system into the JRC experiment and showing the successful isolation of in-band communications and radar waveforms represents a novel step forward in the study of such co-design systems.

8.1 Future Work

While this work serves to demonstrate the feasibility of the Joint Radar-Communications system as described, there is still much work that can be extended. This is mostly predicated on developing a more interesting target to track with the over-the-air Pulse Doppler radar implementation. A mobile target will allow for a more robust receive processing chain with target tracking and radar return prediction. It will also allow for the development of a non-trivial estimation rate (the estimation rate of a static target becomes zero) which lends itself to more informative performance curves.

8.2 Final Thoughts

This paper demonstrates the design and build of a 100MHz Pulse-Doppler radar using the USRP X310 with nothing more than some relatively cheap antennas and amplifiers. The USRP platform offers a useful starting point in implementing the radar into the nominal WISCAnet as designed by Yu et al. (2017) and extending
the results of the JRC experiment conducted by Gutierrez et al. (2017, 2019). Much more can be done to characterize and quantify the performance of the system as it currently exists. As it stands, this paper serves well to demonstrate the viability of the Joint Radar-Communications system based on USRP Software Defined Radios and show the interference suppression capabilities of the implemented SIC algorithm and receive processing chain.
REFERENCES


