

Dual Polarization Radar Signal Processing

First Semester Report
Fall Semester 2006

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Prepared to partially fulfill the requirements for
EE401

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ABSTRACT

Dual polarization radar signal processing is the processing of data with a horizontal and a vertical component obtained from received radar signals. Several issues such as clutter, range ambiguity, and velocity ambiguity need to be addressed when processing data from radars. Joe Hoatam is studying clutter, Aaron Nielsen is studying range ambiguity, and Josh Merritt is studying velocity ambiguity. Radar signal processing is important and utilized in military, weather, and civilian applications.

This semester, we have studied the basics of dual polarization radar signal processing in depth and have recently begun to research techniques to solve the issues involved in the area. Ground clutter can be tackled by using notch FIR or IIR filters. A technique called GMAP can also be utilized in the removal of clutter. Range ambiguity can be addressed using phase coding. Phase codes such as systematic codes and random phase codes were used in the past and today, SZ codes are being implemented for better results. For the problem of velocity ambiguity, multiple pulse repetition frequencies (prf) can be used in conjunction with clustering algorithms and the maximum likelihood detector.

Next semester, we will be simulating these techniques more in depth using a simulation program such as Matlab. After this, we will be proceeding to implement our algorithms on data from the CHILL radar. By the end of next semester, we will have a comprehensive report on our findings and our suggestions to future techniques to be used on these issues.

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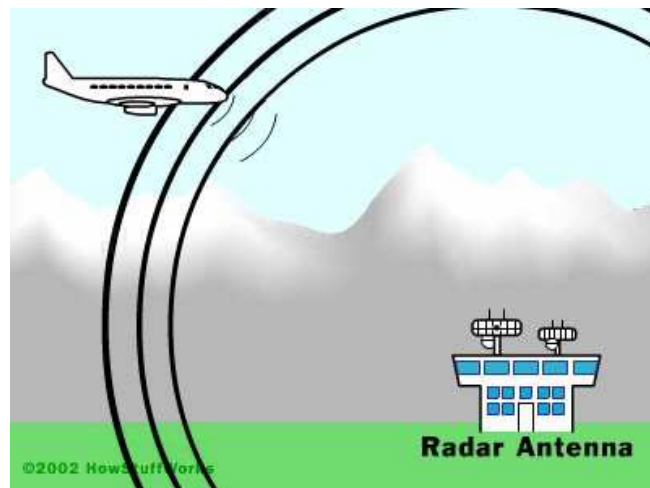
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Chapter I: Introduction

Radar systems today have many different uses. This includes applications in weather, military, and civilian areas. This project focuses on the use of radar in weather applications, as used by CSU's CHILL weather radar.

RADAR, as an acronym, stands for RAdio Detection And Ranging. The basic idea behind radar systems is to send out a signal and listen for an "echo" of this signal off of a target. The first experiments that lead to radar occurred in 1887 by Heinrich Hertz who experimented with wave propagation in air. These experiments led to Christian Huelsmeyer's public demonstration in 1904 by successfully detecting a ship in the nearby harbor. During World War II, there was extensive research performed by American and British agencies, who eventually combined efforts to improve upon existing radar technologies. Following the war, surplus radar systems were picked up for use by other agencies not affiliated with the military, which led to the eventual discovery of Doppler radar systems in 1958. Today, radar is used extensively in applications beyond military, including weather detection.



(Figure 1)

In radar systems, there are two main types of targets – point targets and distributed targets. Point targets are more centralized in space (ie, airplanes), while distributed targets are less centralized (ie, weather patterns). There is a distinction between stationary targets (ie, buildings) versus moving targets (ie, cars), as well. If the target is moving, usage of the Doppler effect can determine how fast the object is traveling.

The Doppler effect, in a nutshell, is a noticeable frequency shift depending on the relative velocities of the target and the observer, usually given as:

$$f' = f_0 \frac{v + v_0}{v - v_s}$$

where f_0 is the initial frequency, v_0 is the velocity of the observer, and v_s is the velocity of the source. An example of this would be a passing police car, blaring its' sirens. As the car nears you, the pitch of the siren will seem to increase, and once it passes, it appears to drop in pitch. However, the siren's frequency didn't change at all. This phenomenon is useful in radar systems, specifically Doppler radar systems. However, for weather radar, the shift in reflected frequency is very, very small, and thus hard to detect. In this case, there is actually a very large shift in the phase of the returned signal in relation to the transmitted wave. By using this idea, we can relate the Doppler effect to phase by realizing that:

$$v(\theta) = \frac{\Delta\theta c PRF}{4\pi f}$$

where $\Delta\theta$ is the difference in phase between the received and transmitted signals, c is the speed of light, and f is the operating frequency of the radar transmitter. The PRF of a radar system only relates to a pulsed-Doppler radar system, as it is the rate at which pulses from the radar are transmitted. The velocity is also able to be calculated in continuous wave systems, but our focus will be exclusively on the pulsed-Doppler radar systems. The signal itself can be modified with

different properties depending on the application used. CSU's CHILL radar is a pulsed Doppler radar.

Some newer pulsed-Doppler radar systems are researching the use of dual wave polarization. By broadcasting a horizontally polarized wave, followed by a vertical polarized wave, reflected signals can be compared to better understand the shape of the target. CSU's CHILL is currently doing research in these dual polarization techniques.

Some inherent problems with radar detection are clutter, range ambiguity, and velocity ambiguity. Clutter refers to noise received by the radar in addition to reflected signals. This noise can come from anything (usually stationary objects), as we witnessed during our visit to CHILL. Jim George pointed the radar towards the highway, not transmitting anything, and showed us the noise created just by passing cars. Another type of clutter is from stationary objects such as the ground or buildings.

Range ambiguity is a situation in radar signal processing where received signals from different ranges appear to have the same range. The maximum range can be determined by the following:

$$r_{\max} = \frac{c \cdot T}{2}$$

where T is the pulse repetition period (which is the inverse of the PRF). The maximum range can be increased by decreasing the PRF, but this also decreases the maximum velocity that can be detected without ambiguity.

Velocity ambiguity is a problem in radar data processing where received signals from different velocities have a phase shift of greater than 2π , thus overlapping and giving false velocity readings. The maximum velocity can be determined by:

$$v_{\max} = \frac{\lambda}{4T}$$

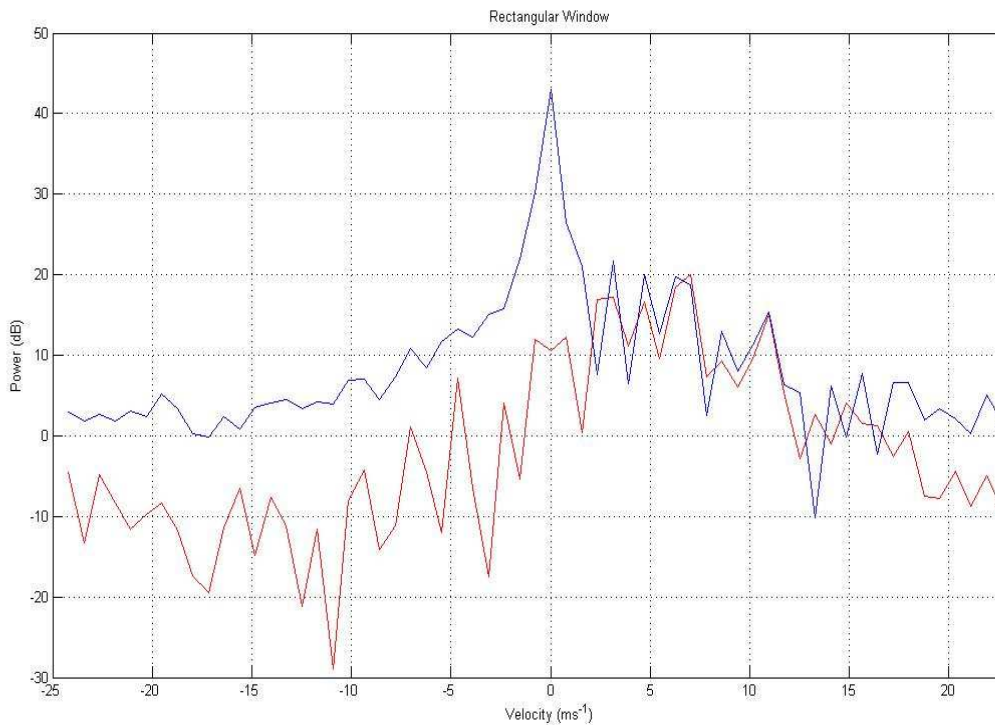
where λ is the wavelength of the transmitted signal. As you can see, from the two equations above, there is a tradeoff between maximum range and velocity, as seen below:

$$r_{\max} \cdot v_{\max} = \frac{c\lambda}{8}$$

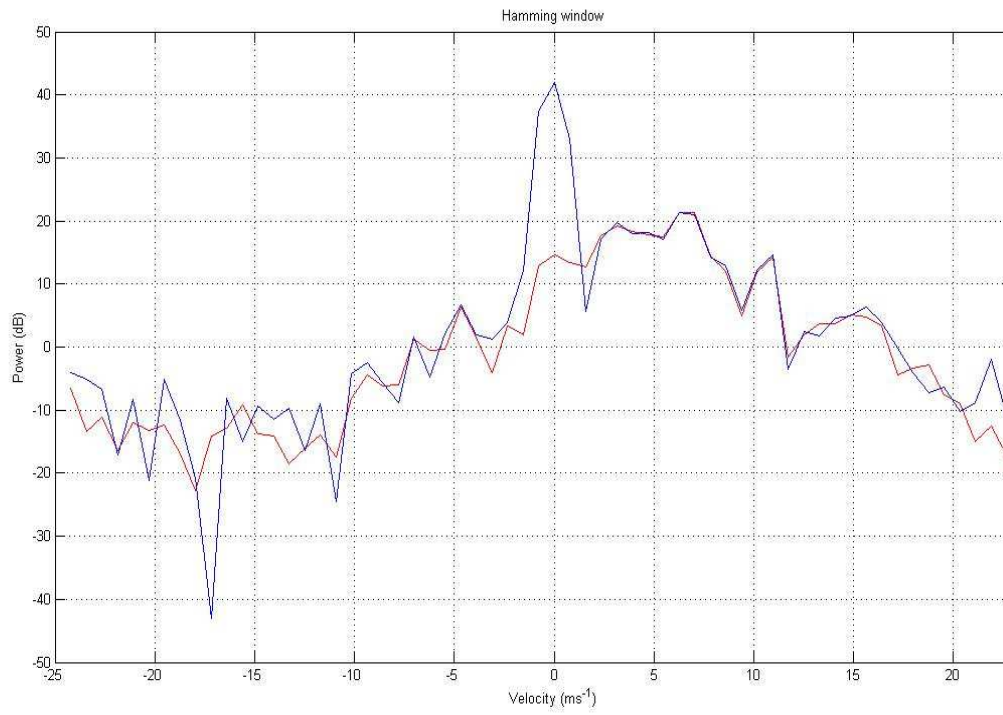
We will be discussing techniques to address these issues, both currently practiced and theoretical, later in the paper.

Chapter II: Simulation Results

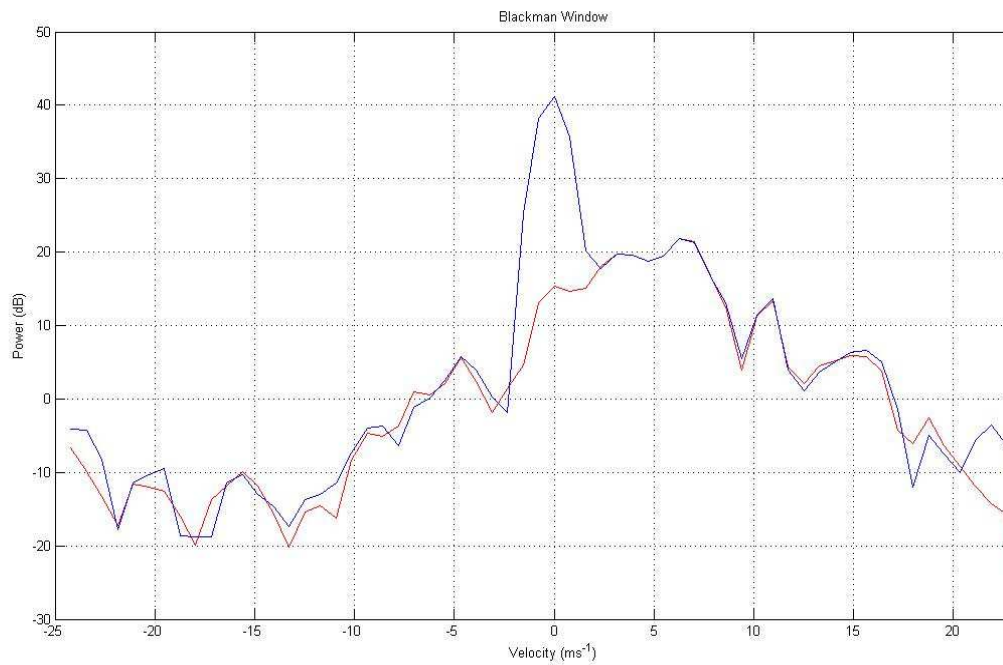
After learning about the basics of radar, we began to run some simulations in Matlab to get some experience with the data processing of radar signals. Our first simulation was to simulate a radar signal with and without clutter. After simulating these results, we plotted them using a variety of windows, including rectangular, Hamming, and Blackman windows. The use of a variety of windows is important to accurately interpret radar data. Below are figures of our simulations of radar data with clutter (in blue) and without clutter (in red) using three different windows.



(Figure 2)



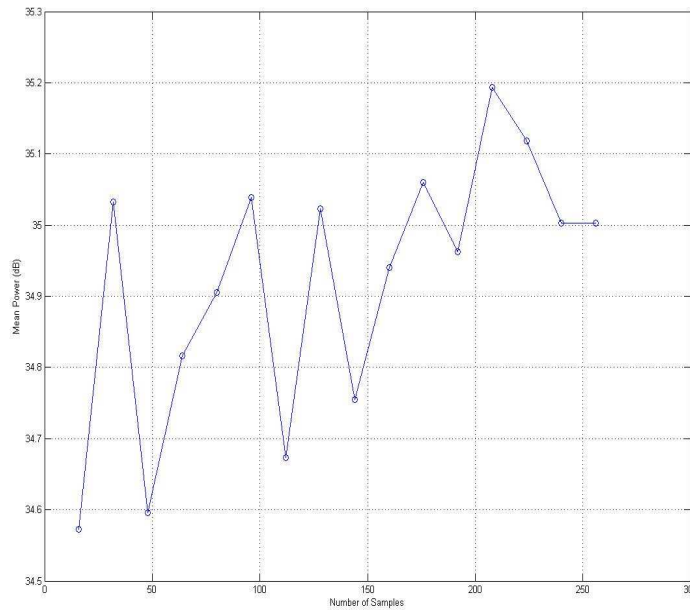
(Figure 3)



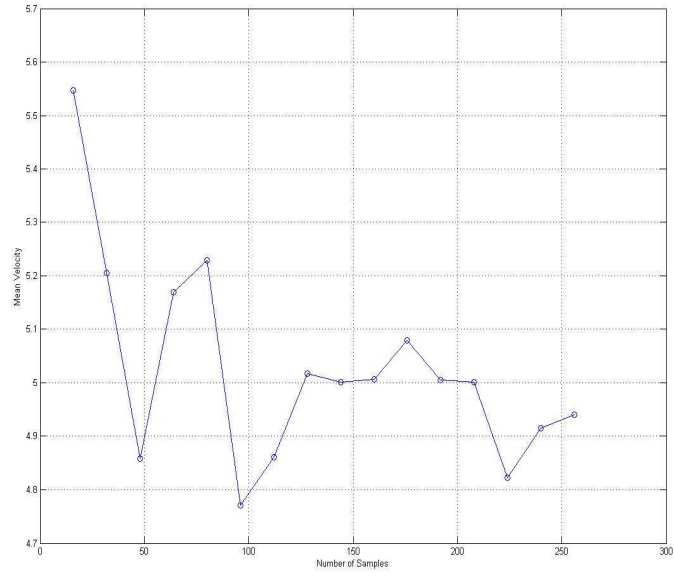
(Figure 4)

Since a rectangular window has a relatively small width for the main lobe in the frequency domain (compared to a Hamming or Blackman window), there are sharper peaks. Since Blackman and Hamming windows have a larger main lobe width, these windows result in smoother results (as seen above). Also, since the side lobes of a rectangular window are relatively large (approximately -13 dB for peak side lobe), clutter will affect the total signal more than the Blackman or Hamming windows (approximately -57 dB and -41 dB, respectively). See Appendix A for details on Matlab code used for this simulation.

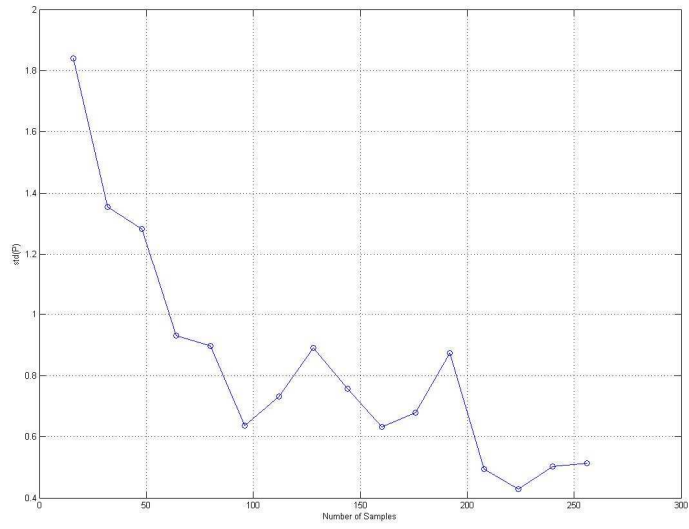
Our next simulation involved altering the number of samples used and viewing the effects on power and velocity calculations. Specifically, we determined the mean and standard deviation of power and velocity for sample sizes of 16 to 256 with a step size of 16. Below are the generated simulation results.



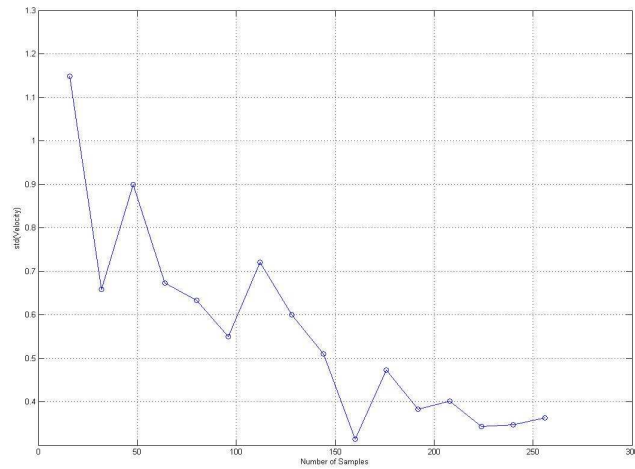
(Figure 5)



(Figure 6)



(Figure 7)



(Figure 8)

As seen above, as the sample size increases, the accuracy of the mean power and mean velocity increases. Additionally, as the sample size increases, the standard deviation of power and velocity decreases. These results matched our predictions of how sample size should affect these parameters. Appendix A contains Matlab code for this simulation.

Chapter III: Problems and Solutions

Now that we've simulated radar signals and have an understanding of various calculations performed on simulated received data, we can begin to analyze our specific problems – clutter, range ambiguity, and velocity ambiguity.

A. Clutter

Clutter is unwanted radar echo. These echoes can “clutter” the radar output and make it hard to detect wanted targets. In particular, ground clutter is undesired radar echoes that come from the ground. Ground clutter is difficult to quantify and classify since radar echo from land depends on many variables that need to be considered before doing anything. Getting rid of clutter or compensating for the loss caused by clutter might be possible by applying appropriate filtering and enhancing techniques [2].

In the past, most weather radar processors have been built using the approach of a fixed notch-width infinite impulse response (IIR) clutter filter followed by time-domain autocorrelation processing called pulse pair modulation. Although this method was widely used there were many drawbacks in using this clutter filtration method. The impulse response of an IIR filter acts just like it sounds, infinite. This means that any perturbations that are encountered, such as a very large point clutter target or change in the pulse repetition frequency (PRF), will affect the filter output for many pulses, sometimes affecting the output for several beam widths. The use of clearing pulses or filter initialization can diminish its effect at the cost of reducing the number of pulses. Another problem is that the filter width used to remove the clutter depends on the strength of the clutter. If the strength of the clutter is very strong then a wider filter must be used. This would be problematic because the filter would either be not aggressive enough for strong clutter or overly aggressive in removing weather echoes.

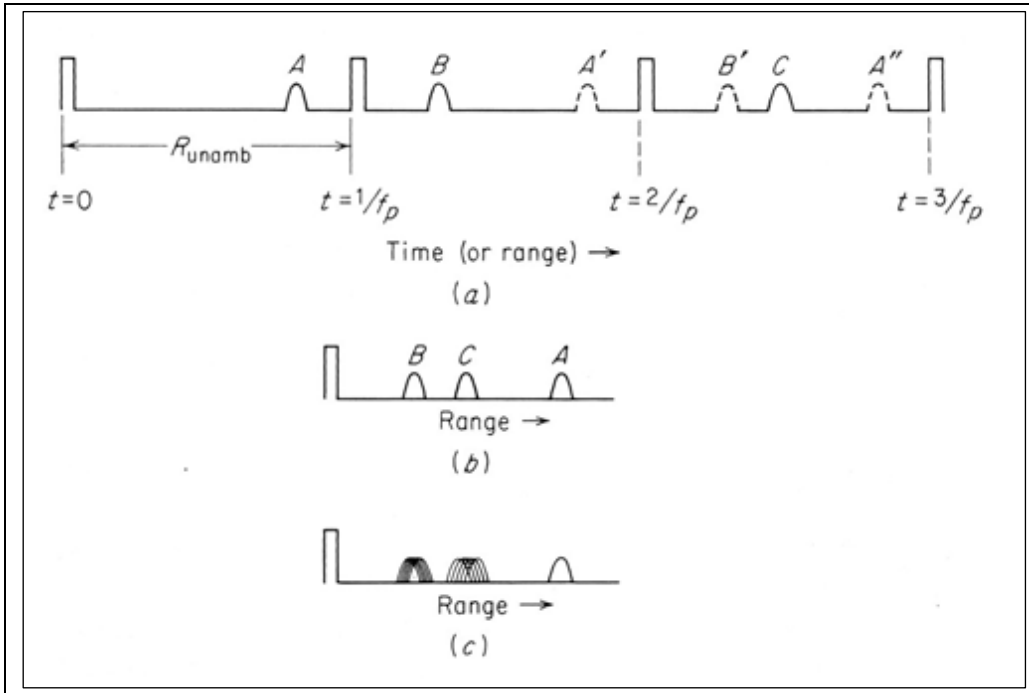
Others have approached the clutter problem by using fast Fourier transform (FFT) processing. The advantage of an FFT approach is that the ground clutter filtering can be made adaptive by searching in the frequency domain to determine the boundary between the system noise level and the ground clutter. The FFT is just a frequency impulse response (FIR) block processing approach that does not have the same problems that the IIR filter has. Just like an IIR filter, the FFT approach has two distinct disadvantages. First, spectrum resolution is limited by the number of points in the FFT, which has the constraint that it must be a power of two. Operational systems are normally either a 32 or 64 point FFT, so if the number of points is low, then clutter will be spread over a bigger part of the Nyquist domain [1]. This can obscure weather targets. The second disadvantage is when a time-domain window is applied to the in-phase I and quadrature-phase Q (IQ) components of the echo prior to performing the FFT in order to get the best performance. The drawback of using windows is that they reduce the number of samples that are processed, which will make the estimates have a higher variance.

The Gaussian model adaptive processing (GMAP) provides many advantages over pulse-air processing with fixed IIR or FIR filters. GMAP is a frequency domain approach that uses a Gaussian clutter model to remove ground clutter over a variable number of spectral components that is dependent on the assumed clutter width, signal power, Nyquist interval, and number of samples. The GMAP approach makes certain assumptions about clutter, weather, and noise. These assumptions include the weather signal's spectrum width is greater than that of the clutter, the Doppler spectrum consists of ground clutter, there is only a single weather target and noise, the width of the clutter is approximately known, and the shape of the clutter and weather is a Gaussian. The way that GMAP works is by applying a Hamming window to the IQ values and then a discrete Fourier transform (DFT) is then performed. The Hamming window is used as the

first guess - after analysis is complete, a decision is made to either accept the results or use a more aggressive window based on the clutter to signal ratio (CSR). Next, the power in the three central spectrum components is summed and compared to the three central components of a normalized Gaussian spectrum. The Gaussian is extended down and all spectral components that fall within the Gaussian curve are removed. Once all the components are removed, a Gaussian is fitted to fill in the clutter points that were removed. This step is repeated until the computed power does not change more than .2dB and the velocity does not change by more than .5% of the Nyquist velocity. Finally, GMAP determines the optimal window based on the values of the clutter to signal values.

B. Range Ambiguity

Range ambiguity is a situation in radar signal processing where received signals from different ranges appear to have the same range. When a pulse is sent from the radar, it must travel, hit an object, and return before the next pulse is sent to avoid range ambiguity. When a pulse is sent and a reflection is not received before the next pulse, an ambiguity in range occurs as illustrated below.



(Figure 9)

As seen above, target B appears to be closer than target A, when in fact, target A is closer than target B.

The maximum range can be determined by multiplying the period of the PRF by the speed of light (speed of propagating waves) and dividing by two to account for a roundtrip.

Below is the general relationship between maximum range and the period of the pulse repetition frequency.

$$r_{\max} = \frac{c \cdot T}{2}$$

As seen above, maximum range is directly related to the period of the PRF and inversely related to the PRF. Allowing the period of the PRF to become very large will increase the maximum range, but will introduce greater velocity ambiguity. As a result, there is a trade off between range and velocity ambiguities when processing data from radars. Depending on the application of the data, one of the two measurements may be more important. Typically, MTI (moving target indicator) radars operate with unambiguous range measurements, but with ambiguous velocity measurements [2]. Pulsed Doppler radars tend to operate with unambiguous Doppler measurements, while having ambiguous range measurements. In our studies, weather data received by the CHILL radar needs to have strong measurements in range and velocity to accurately model weather patterns. Velocity ambiguity will be discussed more in depth later in the chapter.

Techniques have been devised to lower the effects of range ambiguity including a technique called “phase coding”. Phase coding alters the phase of the radar signal before transmission in an attempt to reduce range ambiguities. This phase difference, a_k , is determined by a value Ψ_k , which is determined by the type of phase coding.

$$a_k = \exp(j\psi_k)$$

Phase coding consists of an encoding and a decoding state. In the encoding stage, the signal to be transmitted is multiplied by the phase offset, a_k . The next signal received is then multiplied by a_k^* . If the signal is a first trip signal, then this will make the signal coherent. If,

however, the signal is a second trip signal (it was originally multiplied by a_{k-1}), then it will now be phase modulated by $c_k = a_{k-1} a_k^*$. We will be considering only first and second round trip signals, as this technique can be extended to compensate for further order trips. Additionally, we will consider the first round trip signal to have greater power than the second round trip. Analysis is nearly the same if the opposite is true. Now, depending on the type of code used, one is able to alter the spectra of the two signals. However, before individual codes are examined, a few useful properties of codes will be examined.

Given the situation where a first round trip and a second round trip signal are overlaid, it is helpful if the autocorrelation at lag T is equal to zero (ie, $R(1) = 0$). Since velocity can be calculated by finding the $\arg[R(1)]$, the velocity of the first signal can be calculated without interference from the second signal (as it will have lag T and thus zero autocorrelation). A second useful property when designing codes is the capability to reconstruct signal spectrum from a small part of the original spectrum. This is useful because some filtering of the first signal may occur before the second signal's spectrum is reproduced. Types of codes will now be examined.

The first types of phase coding introduced were systematic phase coding and random phase coding. In a systematic phase coding procedure, the phase difference between successive pulses is uniform. An example of this is using a phase offset of 0 on the first transmitted pulse, a phase offset of $\pi/4$ on the second pulse, and a phase offset of $\pi/2$ on the third pulse. This is the most intuitive type of phase coding, but another type of phase coding was introduced called random phase coding. Depending on the application, random phase coding may be superior to systematic phase coding. Random phase coding simply uses a phase offset that is random between pulses.

A new type of phase coding was developed in recent years called SZ coding developed by M. Sachidananda and D. Zrnic [3]. In this type of phase coding, the phase offset is determined by the number of samples M and a factor n to be chosen, which will affect the period of the code. Below is the formula determining the phase offset in this code.

$$\phi_{(k)} = \psi_{(k-1)} - \psi_{(k)} = n\pi k^2 / M$$

For example, the SZ(8/64) code, has 64 samples and repeats every 8th sample. The SZ code was constructed to have the two properties discussed above: autocorrelation at lag T equals zero and possible spectrum reconstruction from a small portion of the original spectrum. In the case of the SZ(8/64) code, autocorrelation is one at lags of 8, 16...64 and autocorrelation is zero at all other lags. From this property, one can effectively calculate velocity estimates on the first signal without error from the second signal. Once the velocity of the first signal is determined, a notch filter around this velocity can be implemented on the complete signal spectrum. From the resulting signal, the velocity of the second trip signal can be estimated. Simulations conducted by Sachidananda and Zrnic have shown this technique to be superior to random phase coding and systematic phase coding. Velocity ambiguity and techniques to reduce the effects of velocity ambiguity will now be examined.

C. Velocity Ambiguity

Velocity Ambiguity is a problem in radar signal processing where received signals from different velocities have a phase shift of greater than 2π . If this were to happen, the phase from the received signal would end up giving a negative velocity, causing anomalies in the data.

When a signal is sent from the radar, it has a specific phase and power. When it encounters an object, a fraction of the power is reflected and the phase is offset by some amount. This phase shift is measured when the signal is returned and from it, we can figure out the velocity the target is moving at from an earlier discussed equation.

The maximum velocity that can be measured by a radar is given by:

$$V_{\max} = \frac{\lambda}{4T}$$

where λ is the wavelength of the transmitted pulse, and T is the pulse repetition period.

Typically, pulsed Doppler radar systems operate at medium to high pulse repetition frequencies (PRFs), which can offset measurements received by the radar. In past years, there have been techniques that have been developed to help correct these ambiguities, such as a clustering algorithm, which will be discussed here.

A popular choice for radar systems has been the Chinese Remainder Theorem. For accurate measurements, this theorem provides accurate results. However, if there is some range error, then the result could have a very large, incorrect value. To help correct this, a clustering algorithm has been researched and implemented.

This clustering algorithm takes an array of measurements:

$$V_{ki} = V_i + KV_{ai}; \quad K = \frac{-V_{\max}}{V_{ai}}, \dots, \frac{V_{\max}}{V_{ai}}$$

where V_{ai} is the Nyquist velocity for a certain PRF, K is a scalar value from the given range, and V_{max} is the maximum magnitude of the target velocity. Once this vector has been created, we order it from smallest to largest and then find the average squared error of the function by:

$$C_R(j) = \frac{1}{m} \sum_{i=j+1}^{i=j+m} |V_{oi} - \bar{V}|^2$$

where m is the number of consecutive ordered ranges, V_{oi} is the ordered vector of velocity measurements, and \bar{V} is the median value of the data vector. The minimum value of this resulting vector represents the best grouping of data and by taking the ratio of this to the second lowest value, we can find out the overall probability that its' estimate is correct or not [5]. This algorithm has already been implemented over the summer by Joe Weismann and will be double checked before moving onto the next correction technique, the maximum likelihood technique.

The maximum likelihood technique takes an array of data and discriminates between ghost results (ambiguities) and real targets. The results presented in the *Ambiguity Resolution of Multiple Targets Using Pulse-Doppler Waveforms* look promising, as the calculated probability of successfully resolving up to 4 targets for a medium-PRF waveform was essentially 1. It is extendable to high PRF applications as well, with promising success [4].

The total likelihood is a function of the probability of detection, the probability of a false alarm, the measurement error characteristics, and the probability of target resolution on a single PRF, which is a function of the target separation from other targets [6]. This is all very difficult to calculate, since some of these factors are unknown, and implementation is difficult. I do not fully understand all the details of this method yet, but will work with it next semester.

IV. Conclusions and Future Work

This semester we have barely scratched the surface of the problems that others must face on a daily basis. The knowledge that we have picked up so far will help in furthering ourselves for the task ahead of us in the upcoming semester. The problems of clutter, range ambiguity, and velocity ambiguity are not topics that we had learned already in the electrical engineering department but with the help of Professor Chandrasekar, Cuong Nguyen, and Nitin Bharadwaj, we believe that we will be able to analyze data taken by the CHILL radar.

As we have discussed in detail previously, there are different techniques that can be utilized to lower or eliminate the effects of clutter, range ambiguity, and velocity ambiguity. With clutter, FIR and IIR notch filters can be used to eliminate low frequency noise. Also, FFT and GMAP techniques can be used for effective filtering of clutter. Range ambiguity can be dealt with using phase coding. Although different types of phase coding have been introduced in the past twenty years, today, SZ coding has shown in simulations to be the most effective. Finally, velocity ambiguity effects can be lowered using multiple pulse repetition frequencies in conjunction with clustering algorithms and the maximum likelihood estimator. Next semester we will be implementing some of these techniques first in simulation and will proceed to implement these techniques on data from CHILL.

Below we have included a tentative timeline for our work next semester.

<u>Week Number(s)</u>	<u>Activities</u>
0 (Over Winter Break)	Study technical papers more in depth and gain a complete understanding of techniques to be used
1-3	Simulate techniques using Matlab, edit simulations as needed, make conclusions on results
4-5	Begin work with CHILL data, learn the data format, conduct research on data format as needed (review syntax of C)
6-11	Implement algorithms on data from CHILL, test different algorithms, devise conclusions on results
12-13	Complete rough draft of final report, brainstorm on alternative algorithms, collect necessary figures and results for final report, submit report to Nitin for final analysis
14	Final presentation, last revisions of final report, upload all necessary files to website
15	Turn in final paper, completed website

(Table 1)

The above tentative schedule is for our entire group, as we will be following similar timelines next semester, yet there will be some deviation depending on each member's progress. We have allowed quite a bit of flexibility in our schedule to allow for difficulties we may have next semester. For instance, one of the team members may need additional time to work on Matlab simulations before proceeding to implementing them on CHILL data. Josh, who is studying velocity ambiguity, will tentatively research implementing his algorithms on CHILL, but this may prove to be difficult to schedule in conjunction with the staff at CHILL. Additionally, as we begin studying the data format of CHILL to implement our algorithms, we may encounter difficulties working with this format. Aaron and Josh have some experience programming in C, but Joe lacks C experience. He may need additional time to understand the data format. Although we have stated that the paper will be completed as a rough draft by week

13, we will be working on this throughout the semester. The website is also an ongoing project and files are constantly being uploaded, but will be completely done by week 14. Other smaller projects such as working with VCHILL (Java console to visually analyze CHILL data) have not been shown on the plan, but will also be done next semester. We have worked with VCHILL some this semester, but we hope to gain a more thorough knowledge of the program by the end of next semester. Overall, we have a good plan of what we will be working on next semester, but this plan is not comprehensive and can be adapted to deal with technical difficulties.

As we look forward to our work next semester, we see that we have made lots of progress in our studies in Dual Polarization Radar Signal Processing. We began this semester by looking at the basics of radars, types of radars, and some of the problems encountered when analyzing radar data. As the semester ends, we have begun to work independently on our individual projects - clutter, range ambiguity, and velocity ambiguity. Next semester, we have planned a schedule to work on these problems individually and by the end, we will have results on how effective these algorithms work. This semester has been very effective in teaching us the basics of radar and it will be the foundation for our work next semester.

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Appendix

File: bimodal.m

```
% This file creates radar clutter for a given signal that is similar
% to example.m.
% This file calls the simSIG.m file that was provided to us

clc
clear all
close all

%*****
% Input parameters for S-band radar data
f0=3e9;           % Radar frequency in Hz ( X-band ~10 GHz,
                  S-band ~3 GHz)
c=3e8;           % Velocity of light m/s
lambda=c/f0;     % Wavelength in m
prt=1e-3;
prf=1/prt;

fmax=1/(2*prt);  % Nyquits freq.
va=lambda/(4*prt); % Unambiguity radial velocity
rmax=c*prt/2;    % Unambiguity range

m=64;           % Sample size
pn=15;          % Noise power (in dB)
SNR=20;         % Signal to noise ratio (in dB)
p=pn+SNR;       % Signal power (in dB)
v=5;           % Signal velocity (in m/s)
w=4;           % Signal spectrum width (in m/s)

% Dual-polarization parameters
rhoco_P=0.99;   % Co-polar correlation coefficient of
                signal
phidp_P=-50;    % Differential propagation phase in deg
zdr_P=2;        % ZDR for precipitation in dB

win_flag=1;     % Set window effect for simulation program
                (1: apply window effect on the data; 0:
                no)
noise_flag=1;   % Indicate wheather noise is included in
                simulated data or not (1: yes; 0: no)

warning off;
format short;

%*****
% Generate data
% h_ts: time series for H polarization signal
% v_ts: time series for V polarization signal
[h_ts,v_ts]=simSIG(f0,prt,m,p,pn,v,w,zdr_P,phidp_P,rhoco_P,noise_flag,win_flg);
```

```

pn=15;
SNR=40;
p=pn+SNR;
v=0;
w=.1;
[h_clut,v_clut]=simSIG(f0,prt,m,p,pn,v,w,zdr_P,phidp_P,rhoco_P,noise_flag,win
_flag);

h_temp=convn(h_ts,h_clut,'same');
v_temp=convn(v_ts,v_clut,'same');

%*****
% Plot PSD of the signal (Hamming Window)

[Phh,faxis] = periodogram(h_ts,hamming(m),m,fmax);
vaxis=fliplr(linspace(-va+2*va/m,va,m));

Phh=fftshift(Phh);

% Signal with Clutter
[ph_temp,fax_temp]=periodogram(h_temp,hamming(m),m,fmax);
vax_temp=fliplr(linspace(-va+2*va/m,va,m));

ph_temp=fftshift(ph_temp);

figure
subplot(2,2,1), plot(vaxis,dbs(Phh),'r-',vax_temp,dbs(ph_temp))
legend('Red line: Without Clutter','Blue line: With Clutter');
grid on;
xlabel('Velocity (ms^{-1})')
ylabel('Power (dB)')
title('Hamming window')

%*****
% Plot PSD of the signal (Blackman window)

[Phh,faxis] = periodogram(h_ts,blackman(m),m,fmax);
vaxis=fliplr(linspace(-va+2*va/m,va,m));

Phh=fftshift(Phh);

% Signal with Clutter
[ph_temp,fax_temp]=periodogram(h_temp,blackman(m),m,fmax);
vax_temp=fliplr(linspace(-va+2*va/m,va,m));

ph_temp=fftshift(ph_temp);

subplot(2,2,2), plot(vaxis,dbs(Phh),'r-',vax_temp,dbs(ph_temp),'b-')
legend('Red line: Without Clutter','Blue line: With Clutter');
grid on;
xlabel('Velocity (ms^{-1})')
ylabel('Power (dB)')

```

```

title('Blackman Window')

%*****
% Plot PSD of the signal (Rectangular Window)

[Phh,faxis] = periodogram(h_ts,rectwin(m),m,fmax);
vaxis=fliplr(linspace(-va+2*va/m,va,m));

Phh=fftshift(Phh);

% Signal with Clutter
[ph_temp,fax_temp]=periodogram(h_temp,rectwin(m),m,fmax);
vax_temp=fliplr(linspace(-va+2*va/m,va,m));

ph_temp=fftshift(ph_temp);

subplot(2,2,3), plot(vaxis,dbs(Phh),'r-',vax_temp,dbs(ph_temp))
legend('Red line: Without Clutter','Blue line: With Clutter');
grid on;
xlabel('Velocity (ms^{-1})')
ylabel('Power (dB)')
title('Rectangular Window')

```

File: spectrumage.m

```
% DESCRIPTION: creates time series data with length m; calculate and plot the
mean power and mean velocity, as well as the variations of both; uses the
simSIG.m file provided to us for signal generation
% INPUT: power of noise; SNR; velocity; spectrum width.

%*****
% Input parameters for S-band radar data
f0=3e9;           % Radar frequency in Hz ( X-band ~10 GHz, S-band
~3 GHz)
c=3e8;           % Velocity of light m/s
lambda=c/f0;     % Wavelength in m
prt=1e-3;
prf=1/prt;

fmax=1/(2*prt);  % Nyquist freq.
va=lambda/(4*prt); % Unambiguity radial velocity
rmax=c*prt/2;    % Unambiguity range

m=64;            % Sample size
pn=15;           % Noise power (in dB)
SNR=20;          % Signal to noise ratio (in dB)
p=pn+SNR;        % Signal power (in dB)
v=5;             % Signal velocity (in m/s)
w=4;             % Signal spectrum width (in m/s)

% Dual-polarization parameters
rhoco_P=0.99;    % Co-polar correlation coefficient of signal
phidp_P=-50;     % Differential propagation phase in deg
zdr_P=2;         % ZDR for precipitation in dB

win_flag=1;      % Set window effect for simulation program (1:
apply window effect on the data; 0: no)
noise_flag=1;    % Indicate wheather noise is included in
simulated data or not (1: yes; 0: no)

warning off;
format short;

%*****
% Generate data in a two-dimensional array, h_signal(row,column)
% h_ts: time series for H polarization signal
% v_ts: time series for V polarization signal
% Also calculate Mean Power, Mean Velocity
% psd_ts: Mean Power
% vel_ts: Mean Velocity

temp=1;
n_samp=16:16:256; % Sets our X Axis in # of samples
psd_ts=zeros([1,5]);
vel_ts=zeros([1,5]);
std_p=zeros([1,5]);
psd_temp=zeros([25,5]);
vel_temp=zeros([25,5]);
```

```

std_p=zeros([1,5]);
std_v=zeros([1,5]);

for i=16:16:256;
    for j=1:25

[h_ts,v_ts]=simSIG(f0,prt,i,p,pn,v,w,zdr_P,phidp_P,rhoco_P,noise_flag,win_fla
g);
        [h_temp,h_lag]=xcorr(h_ts,1);
        psd_temp(j,temp)=h_temp(2)/i;
        vel_temp(j,temp)=phase(h_temp(3));
    end
    temp=temp+1;
end
vel_temp=abs(vel_temp * lambda/(4*pi*prt));
psd_ts=mean(dbs(psd_temp));
vel_ts=mean(vel_temp);
std_p=std(dbs(psd_temp));
std_v=std(vel_temp);

%*****
% Plots
%

figure
plot(n_samp,psd_ts,'o-');
grid on;
xlabel('Number of Samples');
ylabel('Mean Power (dB)');

figure
plot(n_samp,vel_ts,'o-');
grid on;
xlabel('Number of Samples');
ylabel('Mean Velocity');

figure
plot(n_samp,std_p,'o-');
grid on;
ylabel('std(P)');
xlabel('Number of Samples');

figure
plot(n_samp,std_v,'o-');
grid on;
xlabel('Number of Samples');
ylabel('std(Velocity)');

```

Acknowledgements

This semester we have worked with several students and faculty members that have been extremely helpful in our studies. Our overall guidance for this project was from Dr. Chandrasekar. Two graduate students, Cuong Nguyen, and Nitin Bharadwaj, were responsible for our week to week progress and critique of our weekly presentations. Members of CHILL such as Jim George and Pat Kennedy were helpful in giving us CHILL on-site technical information. Finally, Olivera Notaros provided overall direction. These people have all been very beneficial in our project this semester.