EVALUATION OF BINARY PHASE CODED PULSE COMPRESSION SCHEMES USING AND TIME-SERIES WEATHER RADAR SIMULATOR

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Abstract

In order to evaluate pulse compression for use in phased array weather radar systems, modifications to the Time-Series Weather Radar Simulator have been made which incorporate phase-coding into its functionality. This allows for evaluating the performance of various pulse compression schemes under controlled conditions. In this study, a 5-bit Barker code has been integrated into the TSWRS along with a matched filter to baseline functionality and performance with regard to Integrated Sidelobe Level (ISL). While showing the 5-fold increase in resolution, the results show that an average ISL of -4 dB is produced with this simple design.

1. INTRODUCTION

With the current trend towards fielding phased array radars that utilize low peak-power T/R modules, such as in phased array radars, methods of recovering potentially lost performance are being examined in greater detail. As such, weather radars that incorporate pulse compression technologies are being analyzed to provide equivalent or better performance to those currently in use.

As a phased array weather radar that is capable of incorporating pulse compression was not available, a simplified framework in which the effects of pulse compression on radar returns from meteorological targets could be tested and evaluated was created. This was completed by leveraging off of the work by Cheong et al. [2006] and Xue et al. [2003] whereby a weather radar simulator integrates output from the Advanced Regional Prediction System (ARPS) to initialize itself. The ultimate goal of this research is to identify promising waveform and filter combinations that could offset the loss in peak transmitting power in the Multifunction Phased Array Radar being developed through the National Severe Storms Laboratory [Forsyth and et al, 2006].

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This paper focuses on utilizing binary phase coding in the Time-Series Weather Radar Simulator (TSWRS) to baseline the functionality and performance of a bi-phase code and matched filter processing scheme. The variables under consideration include code length, code type, total pulse duration, and filtering method. We will illustrate the performance of various phase coding and filtering combinations with emphasis placed upon minimizing Integrated Sidelobe Levels (ISL).

2. BACKGROUND

2.1. Pulse Compression

Pulse compression involves transmitting a coded, wideband signal and compressing the return signal through filtering, which results in increased signal power and enhanced range resolution. Phase codes partition the transmitted pulse into equal segments, or subpulses, and then switch the phase of the signal at specified intervals. In particular, binary phase codes switch the phase between two values where an example of a 5-bit bi-phase code is shown in Figure 1. This waveform represents a carrier frequency being modulated in phase every subpulse between 0 and π according to the code [+ + + - +] where + represents a phase of e^{i0} and - represents $e^{i\pi}$. A subpulse is defined as the time duration of one bit so a 5-bit code as shown which is 5 μs in duration will have five 1-μs subpulses.

The amount of compression possible is equivalent to the time-bandwidth product (BT) of the code, which is the product of the signal bandwidth and signal total duration. Bandwidth of a phase-coded signal is calculated via B=1/τ where τ is taken to be the code subpulse length. The returned signal power increase is proportional to the code length while the range resolution is inversely related to bandwidth as shown in Eq. 1. This implies that decreasing subpulse duration results in a corresponding enhancement in range resolution.

$$\Delta R = \frac{c}{2B} \tag{1}$$

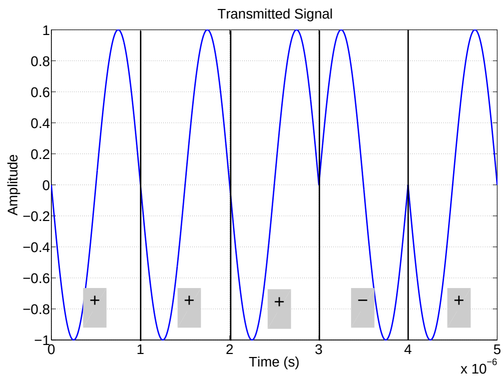

Figure 1: Example of 5-bit Bi-phase Code

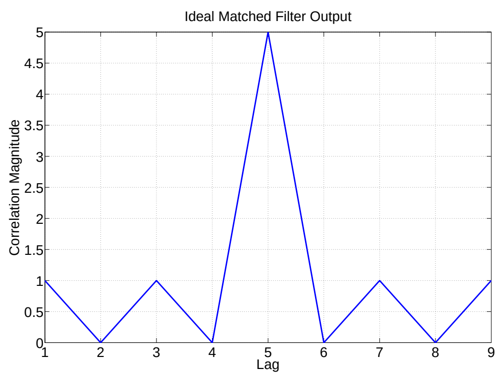

Figure 2: Compressed Phase-coded Waveform through a Matched Filter

The weakness of such systems is in the creation of range sidelobes which are artifacts produced by the compression process whereby returns from other ranges contaminate the signal at the desired range. The resulting output can cause erroneous estimations of reflectivity, mean velocity, and spectral width. Figure 2 shows the decoded output for the waveform shown in Figure 1 if it were passed through a matched filter. In particular, this is one example of a set of codes known as Barker codes which have uniformly distributed sidelobes about the mainlobe [Nathanson, 1999]. Barker codes also have the property of producing mainlobes that are higher than the sidelobes by a factor of the code length. In this case, the code length is 5 bits so the mainlobe is 5 times higher than the sidelobes.

Using output of this type we can calculate two metrics that describe the performance of the filtering process. The first metric is the Integrated Sidelobe Level (ISL), as shown in Eq. 2, which compares the total power contained within the sidelobes to the mainlobe. The second metric is the Peak Sidelobe Level (PSL), calculated via Eq. 3, which compares the sizes of the highest sidelobe to the size of the mainlobe. In both of these equations, x_0 refers to the mainlobe magnitude while x_i refers to all other output range sidelobes except the mainlobe. Improvement for both metrics is indicated by a reduction in their respective values. The ISL is of great importance in weather applications since weather is by nature a distributed phenomena implying that strong gradients in reflectivity can adversely affect sidelobe performance.

$$ISL = 10 \log \sum_{i=1} \frac{x_i^2}{x_0^2} \quad (2)$$

$$PSL = 10 \log \left[\frac{max(x_i)^2}{x_0^2} \right] \quad (3)$$

2.2. Radar Simulator

Data were generated using the Time-Series Weather Radar Simulator (TSWRS) created by Cheong et al. [2006]. The TSWRS is a 3-dimensional radar simulator consisting of an ensemble of thousands of scatterers placed within the field of view of the virtual radar. It is capable of operating in a dish mode akin to a WSR-88D weather radar as well as in a phased array mode. The meteorological fields used as input to the simulator correspond to output data from the Advanced Regional Prediction System (ARPS) numerical simulation model developed at the Center for the Analysis and Prediction of Storms (CAPS) at OU. The spatial and temporal resolution of the ARPS output used in this study was 25 m and 1 s, respectively. To begin the simulation process, scatterer characteristics are initialized from a known ARPS data set. At the next time step, the scatterer positions are updated according to the wind field as well as their corresponding properties at their new locations. The return signal amplitude and phase from each scatterer is then processed via Monte Carlo integration to calculate time series of the desired meteorological parameters. The test case for all simulations consisted of a small time segment of a tornadic supercell thunderstorm as modeled by the ARPS model. Data were gathered using the dish mode of the TSWRS operating in the S-band at 3.2 GHz.

2.3. Simulation Procedure

The simulation begins with the input of ARPS data into the TSWRS and the initialization of the scatterer properties. For the cases performed, 30,000 scatterers were used for the standard resolution case while 150,000

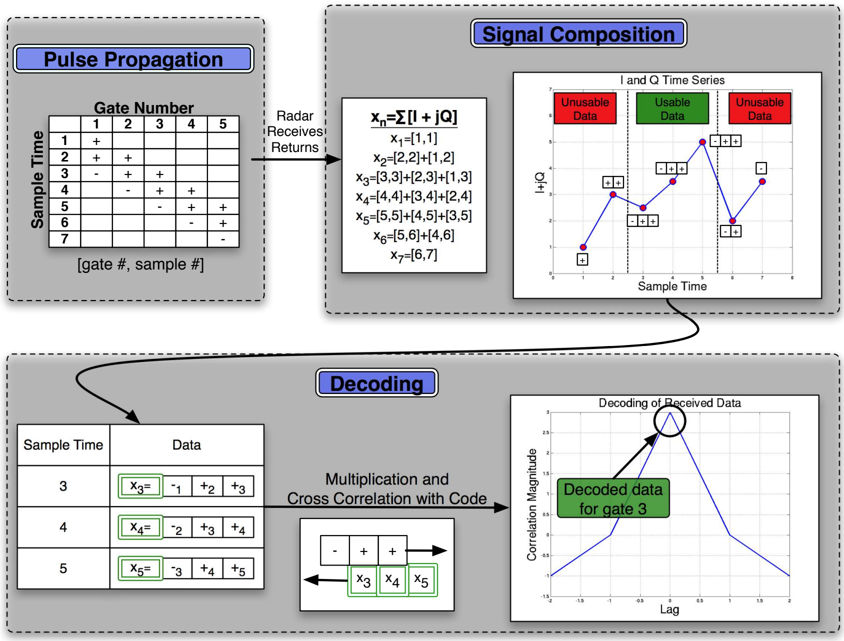

Figure 3: Summary of Simulation Procedure with Matched Filter

scatterers were used for the pulse compression studies. The difference between the number of scatterers is to maintain an average scatterer density of 20 per resolution volume. Next the pulse is propagated throughout the radar field of view on a gate-by-gate basis as shown in Figure 3. The radar then receives the returns from the scatterers and composes the signal. Mathematically, this step can be described by Eq. 4, taken from Mudukutore and Chandrasekar [1998].

$$y[i,j] = \sum_{\forall m+n-1=j} x_i[m,n] \tag{4}$$

After the signal is composed, the simulator decodes the data through the filtering process to produce the data used for estimation of the reflectivity, radial velocity, and spectral width. A signal-to-noise ratio of 70 dB was used for all conditions.

3. RESULTS

Using the method described above, a 5-bit Barker code was incorporated into the simulator for testing the basic functionality of the scheme. Plots of reflectivity factor, radial velocity, and spectral width were created in order to compare them against the standard simulator output and are shown in Figures 4-6. Of interest was the ISL near areas of reflectivity gradients. As expected the most notable difference between the pulse compression output and the standard output is the difference in range resolution. It is readily seen in Figure 4 where the standard output shows differences of 20 dBZ between adjacent cells along a radial. The pulse compression output shows that a more gradual transition occurs between these same areas simply due to an increase in the resolution. Similarly, the radial velocity and spectral width plots using pulse compression show better definition of boundaries.

Of particular interest was the resulting ISL near these high gradient areas as these should show increased ISL. The reason for this is that the subpulses within the entire pulse are sampling different volumes with their respective phase. As the radar receives all of these signals simultaneously, it is unable to determine the appropriate subpulse/signal combination. A simple comparison between ISL (Figure 7) and reflectivity derivative (Figure 8) shows the spatial correlation that exists between the two parameters. Derivatives were calculated using the difference between one gate and the one ahead of it and dividing it by the spatial difference. We note that by using the 5-bit Barker code, we can achieve an average ISL in the range of -4 dB. Increasing the code length should result in a lower ISL level.

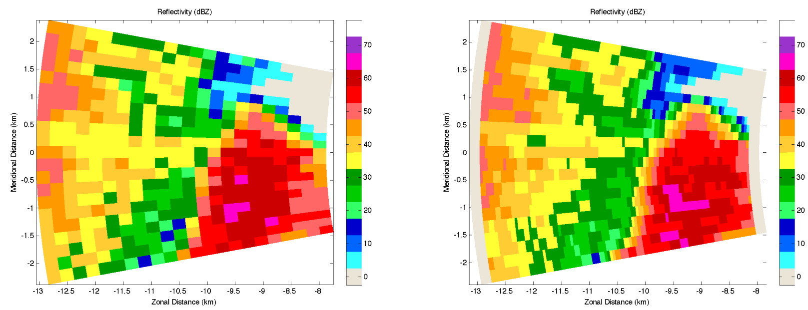

Figure 4: Reflectivity Factor of Standard Output and Output with 5-bit Barker Code & Matched Filter

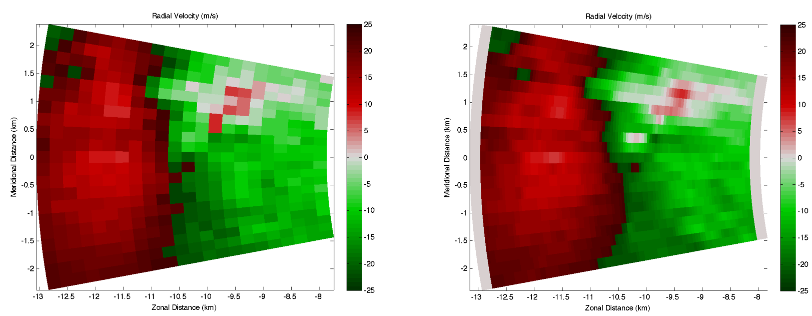

Figure 5: Radial Velocity of Standard Output and Output with 5-bit Barker Code & Matched Filter

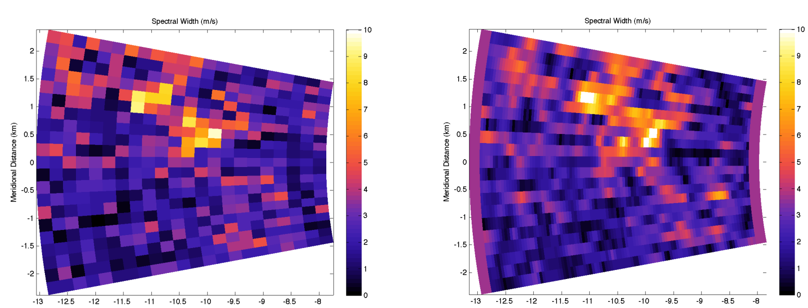

Figure 6: Spectral Width of Standard Output and Output with 5-bit Barker Code & Matched Filter

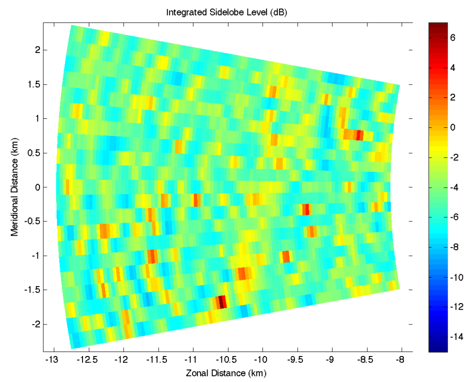

Figure 7: Integrated Sidelobe Level of Radar Field of View

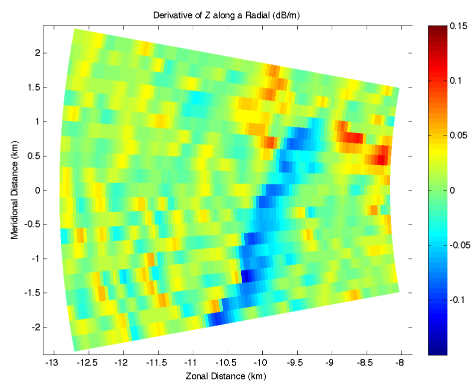

Figure 8: Reflectivity Derivative Along a Radial

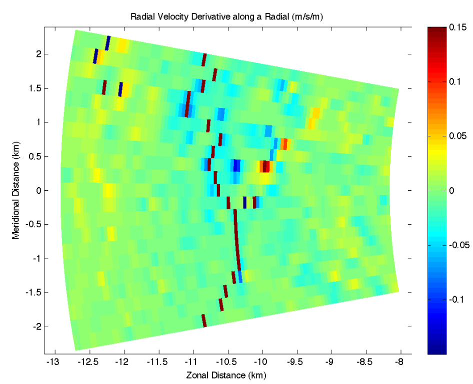

Figure 9: Radial Velocity Derivative Along a Radial

Additionally, velocity also has an effect on the PSL and ISL. The method utilized here with a matched filter implies that the return signal has a uniform velocity across the pulse width. We know this is not the case but present data in Figures 9 to illustrate the relative effects that velocity has on the filtering process. In general, it can be said that higher magnitudes of velocity contribute to increasing both PSL and ISL above the ideal case of no Doppler shift.

From Figures 7-9 we see that the radial velocity component has a lesser impact on the ISL compared to the reflectivity gradients. This can be explained by the small radial velocity gradients within the data set and the relative insensitivity of the matched filter to Doppler shifts caused by small velocity changes.

4. CONCLUSIONS/FUTURE WORK

A successful modification to the TSWRS was presented that produces an increase in range resolution through pulse compression. The simulator currently consists of a 5-bit Barker code with a matched filter which was shown to produce fair performance with respect to ISL. According to the results obtained so far, we note that the simulator reproduces the expected gross effects of showing increased range resolution. Additionally, strong gradients in reflectivity and velocity do produce the expected increase in sidelobe levels. Increased velocities as well as strong velocity gradients were shown to increase integrated sidelobe levels above the -14 dB level expected from a matched filter.

The sidelobe increases shown due to reflectivity and velocity effects indicate a need for a more effective code and filtering process. Of note is the common problem of creating an efficient Doppler tolerant filtering scheme that balances complexity with computational efficiency. The next phase will focus on choosing a more appropriate code than the one used here that increases SNR to a higher level such as a 13-bit Barker code. A scheme will need to be produced that can process data with significant Doppler shifting of the return signal. The last piece includes evaluating filters that will suppress the range sidelobes to much lower levels than those currently achieved with a simple matched filter presented here.

Future iterations using this simulator involve testing and evaluation of additional waveform designs and filtering methods. It is also of great interest to expand the domain size beyond what is currently capable. Ideally we would like to recover resolution back to the WSR-88D standard but are currently limited to only 5 km of data. Transmitting a considerably longer pulse would reduce the number of range gates that could be fully decoded to show a valid comparison between an -88D and a phased array radar incorporating pulse compression.

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