P4D.2

PHASE CODING FOR POLARIMETRIC RADAR

J.C. Hubbert,* NCAR — V. Chandrasekar, Colorado State Univ. — R.J. Keeler, NCAR — N. Bharadwaj, Colorado State Univ.

1. Introduction

The long standing problem of range-velocity ambiguity for pulsed radar system has recently been an area of renewed research (Sachidanada and and Zrnić 1999; Sachidanada and Zrnić 2002; Sachidanada and Zrnić 2003; Frush et al. 2002; Hubbert et al., 2002). The two most promising mitigation techniques have been staggered PRT and phase coding of the transmit pulses. The first method extends both the unambiguous range and velocity by staggering the transmit pulses. Clutter filtering and mitigation of range overlaid echoes has been a major drawback of this method, however recently signal processing techniques have been develop to over come these limitations at least for simulated data. Phase coding of the transmit pulses allows for separation of overlaid multi-trip echoes thus extending the unambiguous range without compromising the unambiguous velocity. Both techniques have been applied to single polarization radars. In this paper the application of these range-velocity mitigation techniques is considered for dual polarization radar system that have the ability to transmit both H (horizontal) and V (vertical) polarization and receive both H and V polarizations simultaneously (i.e., dual receiver). Typical dual polarized radars, such as the S-Pol of the National Center for Atmospheric Research and the CSU-CHILL radar of Colorado State University, alternately broadcast H and V polarized waves and then simultaneously receive H and V polarized returns. For this scheme, second trip echoes are crosspolar signals, third trip echoes are copolar signals, fourth trip echoes are crosspolar signals and so on. The use of phase coding can be used to separate or mitigate the effects of these overlaid echoes.

A new dual polarization scheme has recently appeared in the literature and is currently being tested and considered for deployment on the National Weather Service's NEXRAD radars. The new scheme is based on the fact that raindrop orientation distributions by-in-large have a zero mean canting angle. Thus, H and V polarized waves propagate through rain media without depolarization which leads to very little cross-coupling. There is some cross-coupling since there is depolarization upon backscatter. Thus, H and V polarized waves can be transmitted simultaneously and the received H and V components can be used to estimate quite accurately Z_{dr} (differential reflectivity) and ϕ_{dp} (differential phase) (Doviak et al. 2000). However, LDR (linear depolarization ratio) can not be measured in this scheme since crosspolar signals can not be separated. Phase coding of the transmit pulses will allow for the suppression of the strong copolar signal and separation of the weak crosspolar signal.

To extend the unambiguous velocity, the H and V pulse trains can be staggered. In this paper we show how phase coding combined with staggered H and V pulse trains can be used to simultaneously obtain large unambiguous range and velocity for dual polarization radars.

2. Alternate H and V Transmit

The typical dual polarization radar transmit alternate pulses of H and V polarized waves at equispaced intervals. The result is the measurements of four time series, HH_i, VH_i, VV_i and HV_i as shown in Fig. 1. All moments and polarimetric variables are calculated from these four time series which assume no overlay from multiple trip echoes. Multiple trip echoes can be separated as in the case of a single polarization radar by phase coding the transmit V and H pulses appropriately. One way to phase code the transmit H pulses is with ϕ_i and ϕ_{i-3}, respectively, where ϕ is some systematic switching code (Sachidananda and Zrnić 1999). Fig. 2 illustrates the resulting multiple trip echoes and attached phase code as they would occur when V is the first trip copolar echo. Second trip echoes come from the previously transmitted H pulse and thus is a crosspolar echo. The third trip comes from the previously transmitted V pulse. Obviously, the H and V pulse need be phase coded such that the first second third, etc. echoes have unique phase codes and one way to do this is to phase code the V transmit pulses with ϕ_i and the H transmit pulses with ϕ_{i-3}. If SZ(8/64) phase coding is being used, this would give unique phases for the first 4 trips. However, for SZ(8/64) phase coding, a mutli-trip echo with a phase lag of 4 from the cohered trip will be modulated by SZ(32/64) modulation code and therefore is unrecoverable (Sachidananda and Zrnić 1999).

*National Center for Atmospheric Research, Boulder, Colorado 80307, email: hubbert@ucar.edu

This fourth trip crosspolar signal would likely be very small and not of interest to recover. The copolar V signal can be expressed:

$$\begin{aligned} R_{CO}^{V} &= VV_i\phi_i + VH_{i_1}^{2^{nd}}\phi_{i-3} + VV_{i-1}^{3^{rd}}\phi_{i-1} \\ &\quad + VH_{i-2}^{4^{th}}\phi_{i-4} \end{aligned} \quad (1)$$

where the superscripts indicate the "trip" of the signal. Similarly, the other copolar and crosspolar signals can be expressed,

$$\begin{aligned} R_{X}^{V} &= HV_i\phi_i + HH_{i_1}^{2^{nd}}\phi_{i-3} + HV_{i-1}^{3^{rd}}\phi_{i-1} \\ &\quad + HH_{i-2}^{4^{th}}\phi_{i-4} \quad (2) \\ R_{CO}^{H} &= HH_i\phi_{i-2} + HV_{i}^{2^{nd}}\phi_{i} + HH_{i-1}^{3^{rd}}\phi_{i-3} \\ &\quad + HV_{i-1}^{4^{th}}\phi_{i-1} \quad (3) \\ R_{X}^{H} &= VH_i\phi_{i-2} + VV_{i}^{2^{nd}}\phi_{i} + VH_{i-1}^{3^{rd}}\phi_{i-3} \\ &\quad + VV_{i-1}^{4^{th}}\phi_{i-1} \quad (4) \end{aligned}$$

The signal processing steps for decoding would be similar as it is for single polarization phase coding (See Sachidananda and Zrnić 1999). After phase decoding and obtaining the reconstructed weaker trip time series it remains to be seen how well the polarimetric variables of ϕ_{dp} (copolar differential phase), Z_{dr} (differential reflectivity), LDR (linear depolarization ratio) and ρ_{hv} (copolar correlation coefficient) can be retrieved.

3. Simultaneous H and V Transmit

Another method for obtaining dual polarization measurements is to simultaneously transmit H and V polarized pulses and receive simultaneously both H and V polarizations. This scheme is currently being considered by the National Weather Service for deployment on the NEXRAD radars. With this scheme all copolar variables are recovered, however, LDR can not be estimated since the crosspolar powers are mixed in with the much stronger copolar powers and can not be separated. If however, the H and V transmit pulses can be separately phase coded, it then becomes possible to retrieve LDR. The signal recovery process is more complicated since for the same number of trip rings considered, there will be twice as many overlaid possible signals, i.e., there will both copolar and crosspolar signals to contend with at each range ring. Nevertheless, since LDR is typically not less than 30 dB down from the copolar signal, the crosspolar power will typically be recoverable especially in the case of no multiple trip echoes. It remains to be seen how effectively LDR can be recovered for the case of one copolar trip overlay. A disadvantage of this scheme is that two transmitters are required since current technology does not provide for the reliable phase shifting of high power rf (radio frequency) pulses required for S- or C-band weather radars. The implementation costs may out weigh the benefits for this case. But two transmitters would also allow for the measurement of both crosspolar powers, a capability that the current NEXRAD single transmitter design does not provide. As shown in Hubbert et al. (2003), by measuring both crosspolar powers and sun calibrations, Z_{dr} can be calibrated very precisely without relying on assumptions about the precipitation. If the H and V pulse trains are staggered slightly by say 100μs, then there are added benefits that make two transmitters more attractive.

4. Staggered H and V Pulse Trains

Instead of transmitting simultaneous H and V pulses, the H and V pulse trains could be staggered by a small amount of time. The H and V pulse trains are illustrated in Fig. 3 where the phase ϕ is a possible way to phase code the transmit pulses for the separation of crosspolar echoes and multi-trip echoes. The time T_1 is relatively short (a tenth or less) compared to T. But first we concentrate on the separation of ϕ_{dp} and velocity phases. There are several possible ways to estimate phase based on time lags of T, T_1, $T - T_1$ and $T + T_1$. As for the staggered PRT technique for single polarization radars, the phase estimates for different time lags may allow for the extension of the unambiguous velocity range. It can be shown that,

$$\begin{aligned} \arg\{\langle VV_i VV_{i+1}^* \rangle\} &= -\alpha_T && (5) \\ \arg\{\langle VV_i HH_{i}^* \rangle\} &= \phi_{dp} - \alpha_{T_1} && (6) \\ \arg\{\langle VV_i HH_{i-1}^* \rangle\} &= \phi_{dp} + \alpha_{T-T1} && (7) \\ \arg\{\langle VV_i HH_{i+1}^* \rangle\} &= \phi_{dp} - \alpha_{T+T1} && (8) \end{aligned}$$

where all times series are first trip and α represents the various phases due to velocity for the different subscript time intervals. As can be seen, the velocity based on the short time interval T_1 is embedded in these equations along with ϕ_{dp}. If ϕ_{dp} can be separated, then a velocity estimate with a very high Nyquist velocity would be available based on a PRT of T_1. To separate the velocities and ϕ_{dp} in Eqs.(5) to (8) the following algorithm can be used. Let the Nyqiust velocity for a PRT of T be N_q.

1. From (5) calculate the velocity, $\mathcal{V}_T$. The true velocity, $\mathcal{V}_A$, then must be one of the velocities $\mathcal{V}_A = \mathcal{V}_T \pm n2N_q$ where n is an integer.

2. For each n calculate the phase α_{T-T_1} via $\mathcal{V}_{T-T_1} = \lambda\ \alpha_{T-T_1}/(4\pi(T-T_1))$.
3. Eliminate α_{T-T1} from (8) using these calculated values. This then yields "guesses" for ϕ_{dp}.
4. Use these guesses for ϕ_{dp} to isolate α_{T_1} in (6).
5. Calculate $\mathcal{V}_{T_1}$. If $\mathcal{V}_{T_1} = \mathcal{V}_T \pm n2N_q$ for the assumed value of n, then the correct velocity has been determined, i.e., $\mathcal{V}_A = \mathcal{V}_T \pm n2N_q$.

This method may give unwrapped velocities up to the Nyquist velocity corresponding to a PRT of T_1 which can be very small, however, more testing and verification is needed. For example, if $T_1 = 100\mu$s, the Nyquist rate would be 250 m/s for 10 cm wavelength. This velocity measurement would be noisy since the time interval is very small but it only has to accurate enough to place the velocity estimate $\mathcal{V}_T$ into the correct Nyquist interval. Thus, by staggering the H and V pulse trains, we have achieved unambiguous velocity retrieval for weather precipitation targets. Note that no restriction has been placed on the PRT of the H and V pulse trains. Their PRT could be extended to 3 ms thus giving an unambiguous range of 450 km while maintaining a Nyquist velocity of 250 ms! Since the H and V pulse are phase coded separately, the crosspolar powers are also retrievable.

If the separation of ϕ_{dp} and velocity can not be done by the above method, then alternately, two blocks of pulse trains could be used: 1) as shown in Fig.3 followed by 2) a block where H an V pulses are switched from as they as shown in Fig. 3. (i.e., H and V pulses trade places). It would then become straight forward to separate ϕ_{dp} and velocity and thus obtain a velocity estimate based on the time interval T_1.

Acknowledgment This research was supported by the ROC (Radar Operations Center) of Norman OK and by the National Science Foundation grant ATM-0121546.

References

Doviak, R.J., V.N. Bringi, A. Ryzhkov, A. Zahrai,and D.S. Zrnić, 2000: Polarimetric Upgrades to operational WSR-88D radars *JTECH*, **17**, 257-278.

Frush, C., R.J. Doviak, M. Sachidananda and D.S. Zrnić, 2002: Application of the SZ Phase Code to Mitigate Range-Velocity Ambiguities in Weather Radars, *JTECH*, **19**, 413-430.

Hubbert, J.C, Bringi, V. N., Brunkow, D. 2003: Studies of the Polarimetric Covariance Matrix. Part I: Calibration Methodology, *JTECH*, **20**, 696-706.

Hubbert, J.C. G. Meymaris and R.J. Keeler, 2003: Range-Velocity Mitigation via SZ Phase Coding with Experimental S-band Radar Data, *31st Radar Meteorology Conference*, Seattle WA.

Sachidananda, M. and D.S. Zrnić, 1999: Systematic Phase Codes for Resolving Range Overlaid Signals in a Doppler Weather Radar *JTECH*, **16**, 1351-1363.

Sachidananda, M. and D.S. Zrnić, 2002: An Improved Clutter Filtering and Spectral Moment Estimation Algorithm for Staggered PRT Sequences, *JTECH*, **19**, 2009-2019.

Sachidananda, M. and D.S. Zrnić, 2003: Unambiguous Range Extension by Overlay Resolution in Staggered PRT Technique, *JTECH*, **20**, 673-684.

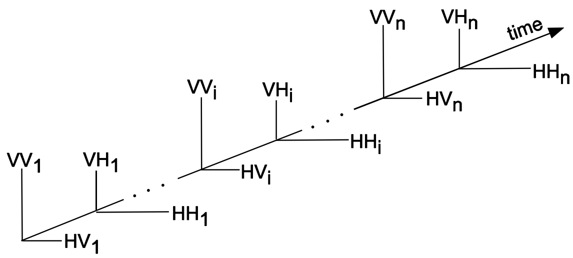

Figure 1: *A schematic of the four measured time series measure with a dual alternating H and V polarization radar. All signals are first trip.*

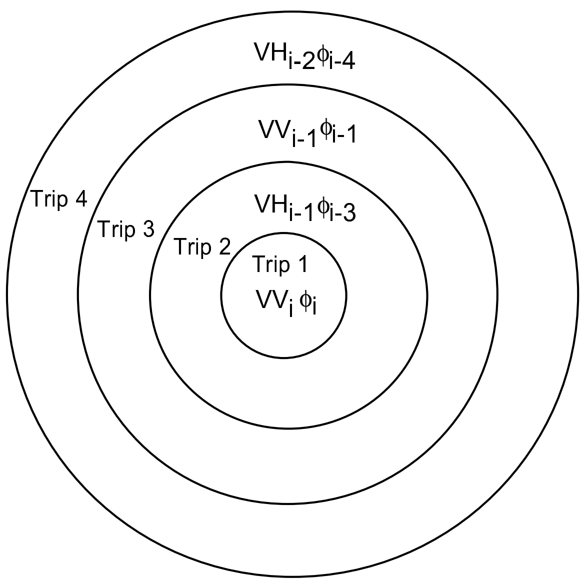

Figure 2: Multiple trips rings for a dual alternating H and V polarization radar.

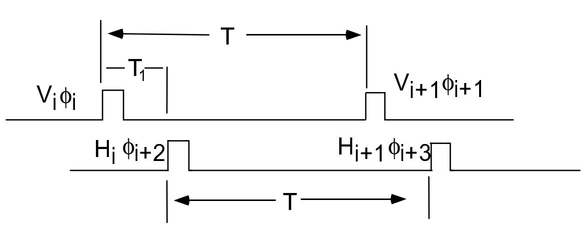

Figure 3: Phase coding and timing for staggered H and V pulse trains.