P7.10 ORTHOGONAL CHANNEL CODING FOR SIMULTANEOUS CO-AND CROSS-POLARIZATION MEASUREMENTS

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ABSTRACT

Polarimetric variables are an essential part of algorithms for improved rainfall rate estimation, attenuation correction and hydrometeor identification. In such systems the transmit polarization state changes according to some fixed pattern that is repeated. The simultaneous mode and alternating mode waveforms are commonly used in weather radars. In the simultaneous mode of operation the horizontal and vertical polarization states are transmitted simultaneously and samples of both horizontal and vertical co-polar return are obtained A drawback of the current implementation of simultaneous mode is its inability to measure cross-polar parameters such as linear depolarization ratio. In this paper a technique to estimate cross-polar signals with a simultaneous mode waveform is presented. In this method, the horizontally and vertically polarized transmit waveforms are coded with orthogonal phase sequences. The performance of the phase coded waveform is determined by the properties of the phase codes. This paper presents the performance of the cross-polar and co-polar parameter estimation based on the simulation as well as data collected from CSU-CHILL radar.

1 INTRODUCTION

Dual polarized measurements of precipitation have been a subject of research for more than a decade and have been demonstrated to provide better rainfall estimates when compared to those estimated from conventional reflectivity. In addition the dual-polarized parameters enable hydrometeor identification and classification. Pulse Doppler weather radars with polarization diversity can transmit and/or receive in two orthogonally polarized channels. In a conventional dual-polarized radar the transmitted pulses are horizontally(H) and vertically(V) polarized forming a linear basis. Polarization diversity refers to the ability of the system to transmit/receive orthogonally polarized waves. Such systems transmit a single polarization state and can receive co and cross-polar components with dual receivers. CSU-CHILL radar system is capable of transmitting horizontal and vertical polarization states simultaneously. Two orthogonally polarized waves are transmitted using two separate (but identical) transmitters with dual channel reception of orthogonally polarized waves. The intrinsic backscattering properties of the hydrometeors to the two polarization states enables the measurement of characteristics such as size, shape and spatial orientation of the precipitation particles in the radar resolution volume. These characteristics are described in terms of the backscattering matrix. The backscattering covariance matrix of particles within a resolution volume is given by Bringi and Chandrasekar (2001)

$$\mathbf{\Sigma}_{BSA} = \left\langle \begin{bmatrix} |S_{hh}|^2 & \sqrt{2}S_{hh}S_{hv}^* & S_{hh}S_{vv}^* \\ \sqrt{2}S_{hv}S_{hh}^* & 2|S_{hv}|^2 & \sqrt{2}S_{hv}S_{vv}^* \\ S_{vv}S_{hh}^* & \sqrt{2}S_{vv}S_{hv}^* & |S_{vv}|^2 \end{bmatrix} \right\rangle \tag{1}$$

where S_{hh}, S_{hv}, S_{vh} and S_{vv} are the elements of the scattering matrix, n is the number of particles per unit volume and the angle brackets denote ensemble averaging. The subscripts "$vh(hv)$" refers to "transmit horizontal(vertical) polarization and receive vertical(horizontal) polarization" and $*$ indicates complex conjugate. The elements of the backscattering covariance matrix or some combination of them are used to compute the polarimetric variables. Meteorological moments and polarimetric variables are estimated from the covariance matrix of the vector of received signals. The received signal **Z** and the corresponding covariance matrix **K** is given by Bringi and Chandrasekar (2001)

$$\mathbf{Z} = \begin{bmatrix} V_{hh} & V_{hv} & V_{vh} & V_{vv} \end{bmatrix}^T \tag{2}$$

$$E\mathbf{ZZ}^H = \mathbf{K} = E \begin{bmatrix} |V_{hh}|^2 & V_{hh}V_{vh}^* & V_{hh}V_{hv}^* & V_{hh}V_{vv}^* \\ V_{vh}V_{hh}^* & |V_{vh}|^2 & V_{hh}V_{hv}^* & V_{vh}V_{vv}^* \\ V_{hv}V_{hh}^* & V_{hv}V_{vh}^* & |V_{hv}|^2 & V_{hv}V_{vv}^* \\ V_{vv}V_{hh}^* & V_{vv}V_{vh}^* & V_{vv}V_{hv}^* & |V_{vv}|^2 \end{bmatrix} \tag{3}$$

where H means Hermitian operator and T indicates transpose. Polarization diversity enables us to measure differential reflectivity, differential propagation phase (or specific differential phase) and linear depolarization ratio. These multi-parameter radar observations

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have been used to measure the bulk properties of hydrometeors in a resolution volume. These polarimetric parameters are an essential part of algorithms for improved rainfall rate estimation, attenuation correction and hydrometeor identification (Bringi and Chandrasekar, 2001).

2 PROBLEM STATEMENT

The linear depolarization ratio is defined as

$$LDR_{vh} = 10\log\left(\frac{\langle \mid S_{vh}\mid^2\rangle}{\langle \mid S_{hh}\mid^2\rangle}\right) = 10\log\left(\frac{\langle \mid V_{vh}\mid^2\rangle}{\langle \mid V_{hh}\mid^2\rangle}\right) \tag{4}$$

where $\langle \mid V_{vh}\mid^2\rangle$ is the cross polar signal power. The linear depolarization ratio provides valuable information when precipitation is mixed with frozen precipitation. Oblate particles with nonzero canting angles or mixed phase precipitation yield a significant amount of cross polarized return. Measurements of LDR is essential for the hydrometeor classification (Liu and Chandrasekar, 2000) and studying mixed phase precipitation. In a polarization diverse system operating under hybrid or simulataneous mode of operation simultaneous observations of the resolution volume are made with both horizontal and vertical polarization states. Simultaneous mode offers a number of advantages over alternate mode (switching between H- and V-polarization on a pulse to pulse basis) (Doviak et al., 2000; Bringi and Chandrasekar, 2001). However, the cross-polar signals $V_{vh}[n]$ and $V_{hv}[n]$ are not available in simultaneous transmission mode and therefore measurements of LDR are not available. Giuli et al. (1993) suggested orthogonal signal using chirp waveforms to measure the cross-polar signal. In this paper a technique to estimate the linear depolarization ratio in simultaneous transmission mode is presented. Coding the transmit waveforms in the H-and V-channel on a pulse by pulse basis enables the retrieval of linear depolarization ratio.

3 WAVEFORM CODING

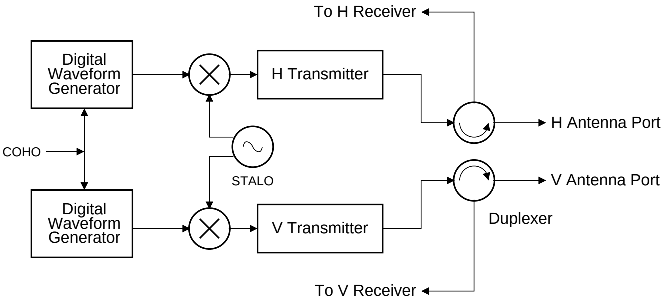

Figure 1: Illustration of effect of orthogonal coding on the co-polar signal spectrum contaminated with cross-polar signal.

Systems with two transmitters such as CSU-CHILL (Fig. 1) can generate and transmit orthogonally coded pulses in the horizontal and vertical polarization channels. The CSU-CHILL radar's klystron transmitters enables the use of phase coding to transmit orthogonal waveforms. A different coding mechanism at the high power RF side was suggested by Stagliano et al. (2006). Phase sequences with defined properties find applications in many engineering applications such as radars ,channel estimation and cryptography. In this paper the two channels (H and V) are orthogonally coded using phase sequences. The received signal from an orthogonally coded H-channel and V-channel transmit pulse is given by

$$\begin{aligned} S_{rh}(k) &= V_{hh}(k)e^{j\psi_h(k)} + V_{hv}(k)e^{j\psi_v(k)} \quad (5)\\ S_{rv}(k) &= V_{vv}(k)e^{j\psi_v(k)} + V_{vh}(k)e^{j\psi_h(k)} \quad (6)\end{aligned}$$

The cross-polar signals are phase modulated by $\phi_h(k) = \psi_v(k) - \psi_h(k)$ and $\phi_v(k) = \psi_h(k) - \psi_v(k)$ in the H-channel and V-channel respectively after recohering with the appropriate codes. The received signals after decoding is given by

$$\begin{aligned} S_h(k) &= V_{hh}(k) + V_{hv}(k)e^{j\phi_h(k)} \quad (7)\\ S_v(k) &= V_{vv}(k) + V_{vh}(k)e^{j\phi_v(k)} \quad (8)\end{aligned}$$

The effect of the code on the cross-polar signal depends on the properties of the phase codes used. The cross-polar signal is whitened if a random phase code is used and modulated to a known form if a systematic code is used. In this paper we consider random phase coding and Walsh coding to retrieve the cross-polar signal. The Walsh code is generated as

$$\mathbf{H}_{2n} = \left[\begin{array}{cc} \mathbf{H}_n & \mathbf{H}_n \\ \mathbf{H}_n & \bar{\mathbf{H}}_n \end{array}\right] \tag{9}$$

where $\bar{\mathbf{H}}_n$ is the complement of $\mathbf{H}_n$ and

$$\mathbf{H}_2 = \left[\begin{array}{cc} 1 & 1 \\ 1 & -1 \end{array}\right] \tag{10}$$

The impact of random and Walsh coding on the received signal is shown in Fig. 2. The received signal has a cross-polar signal which is 20 dB below the co-polar signal and a slightly wider spectral width. The Walsh code modulates the cross-polar signal such that the cross-polar signal is translated by π (or Nyquist velocity) with respect to the co-polar signal in the spectral domain while the random code whitens the cross-polar signals as seen in Fig. 2. The cross-polar signal is obtained by notch filtering the co-polar signal spectral coefficients. Since the cross-polar signal is always lower in power than the co-polar signal the notch filtering can be performed easily for both random code and

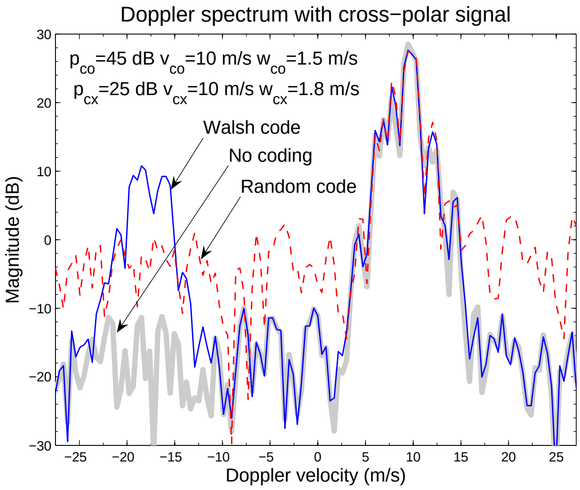

Figure 2: Illustration of effect of orthogonal coding on the co-polar signal spectrum contaminated with cross-polar signal.

Walsh coded signal. The cross-polar signal power is estimated from the notch filtered signal. A simulation at $\lambda = 11.01$ cm is performed to evaluate the performance of the coding scheme to retrieve the linear depolarization ratio. The bias in $L\hat{D}R_{vh}$ estimated in simultaneous transmission mode as a function true LDR_{vh} is shown in Fig. 3. A r.m.s phase error of 0.5 degree is added to the transmit pulses in the two channel and true phase codes are used in decoding the received signals. The cross-polar signal spectral width is generally larger than co-polar signal spectral width. Hence the cross-polar signal spectral width is set to one and a half times the spectral width of co-polar signal ($\sigma_v = 4$ m/s). The bias in $L\hat{D}R_{vh}$ indicates that the Walsh coded waveform has better performance in retrieving the cross-polar signal. Although the use Walsh code indicates that LDR below -34 dB can be estimated within a 1 dB the lower bound of measurable LDR is limited by the antenna cross-polarization isolation. The CSU-CHILL system has a lower bound of -34 dB (Brunkow et al., 2000) based on the antenna pattern and measurements have shown values in the -33 to -34 dB range.

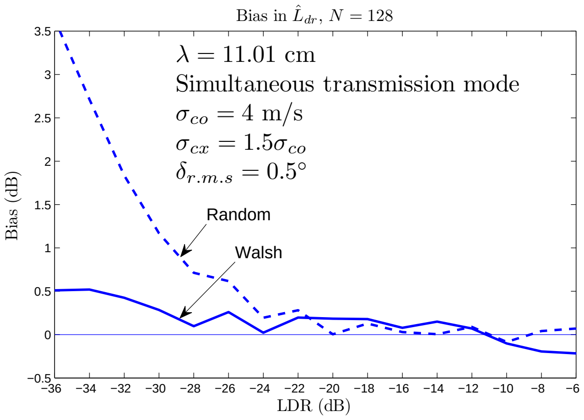

Figure 3: Bias in $L\hat{D}R_{vh}$ using phase coding as a function of true LDR_{vh} with a r. m. s phase error of 0.5$\circ$ at $\lambda = 11.01$ cm.

4 DATA ANALYSIS

Orthogonally coded horizontal and vertical polarization channels were used to collect data from a CSU-CHILL radar. Modulated RF drive pulses for each transmitter are synthesized by the transmitter controller. The transmitter controller uses a digital upconverter chip to synthesize a modulated IF frequency and the resulting IF signal is upconverted to S-band. All internal data paths are 16 bits or greater and this allows the r.m.s phase error to be negligible as shown in Fig. 4. The phase measurements shown in Fig.4 were estimated based on returns from a hard target (tower) using a phase coded waveform with CSU-CHILL radar. Radar data on a stratiform event with phase coded waveform was collected from the CSU-CHILL radar on May 29, 2007. In addition data using alternate transmission mode was also collected. Alternate mode of operation enables the direct measurement of linear depolarization ratio. Both the alternate mode and phase coded waveform data were collected with an RHI scan at an azimuth of $80°$. Figure 5 shows the RHI of estimated reflectivity from alternate mode and phase coded simultaneous transmission mode. The increase in reflectivity from the surface up to the melting layer clearly indicates an occurrence of a bright band at an altitude of 1.8 km. The LDR_{hv} estimated from alternate mode and simultaneous mode with Walsh code is shown in Fig. 6 respectively. The bright band can be clearly identified by the enhance depolarization ratio in Fig. 6. The alternate mode LDR is used as a reference to compare the LDR estimated

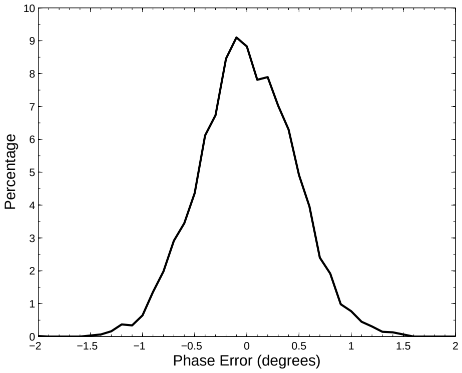

Figure 4: Histogram of phase error measured with the CSU-CHILL radar.

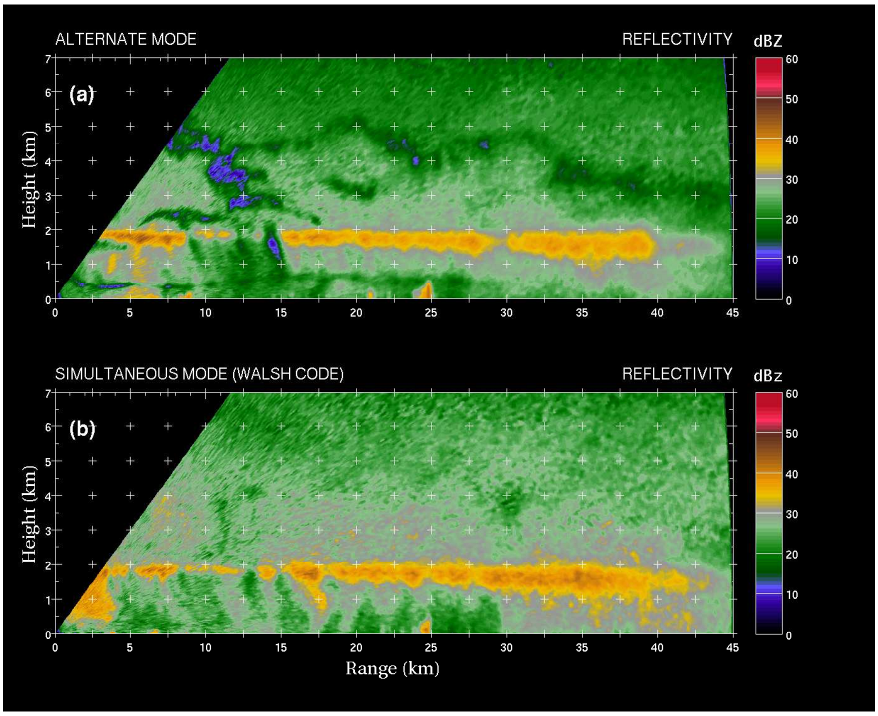

Figure 5: Reflectivity measurements from alternate mode and simultaneous mode. Data collected from CSU-CHILL radar on 29 May, 2007 with alternate mode (20:34:00 UTC) and Walsh coded simultaneous mode (20:28:51 UTC). (a) Alternate mode (b) Simultaneous mode with Walsh code.

from the phase coded waveform. The absolute difference in measurements between alternate mode and simulataneous mode is attributed to the time difference between data collections. The LDR_{hv} estimated from Walsh coded waveform is very similar to the LDR_{hv} estimated from alternate mode except in the region contaminated by ground clutter. An IIR filter is used to remove ground clutter in alternate mode while spectral filter is used to filter ground clutter in Walsh coded waveform. The LDR_{hv} measured from coded waveforms in simulataneous mode closely matches the LDR_{hv} from alternate mode and can retrieve LDR_{hv} upto -28 dB.

5 SUMMARY

Phase coding the transmit waveform in the horizontal and vertical polarization channels on a pulse to pulse basis can be used to retrive linear depolarization ratio in simultaneous transmission mode. Random and Walsh phase coded waveforms were considered in this paper for retrieving LDR. A simulation was performed to compare the ability of the phase coded waveform to retrieve LDR and it is observed that Walsh coded waveform performs better than the random phase coded waveform. The ability to retrieve LDR is limited by the cross-polar isolation of the antenna. LDR measurements obtained by CSU-CHILL with alternate mode show values in the -32 to -34 dB interval. Data collected by the CSU-CHILL radar shows that LDR estimated from phase coded waveform is comparable to the LDR estimated from alternate mode and can retrieve LDR_{hv} upto -28 dB.

ACKNOWLEDGMENT

This work was supported the National Science Foundation through the National Science Foundation (NSF) ITR program.

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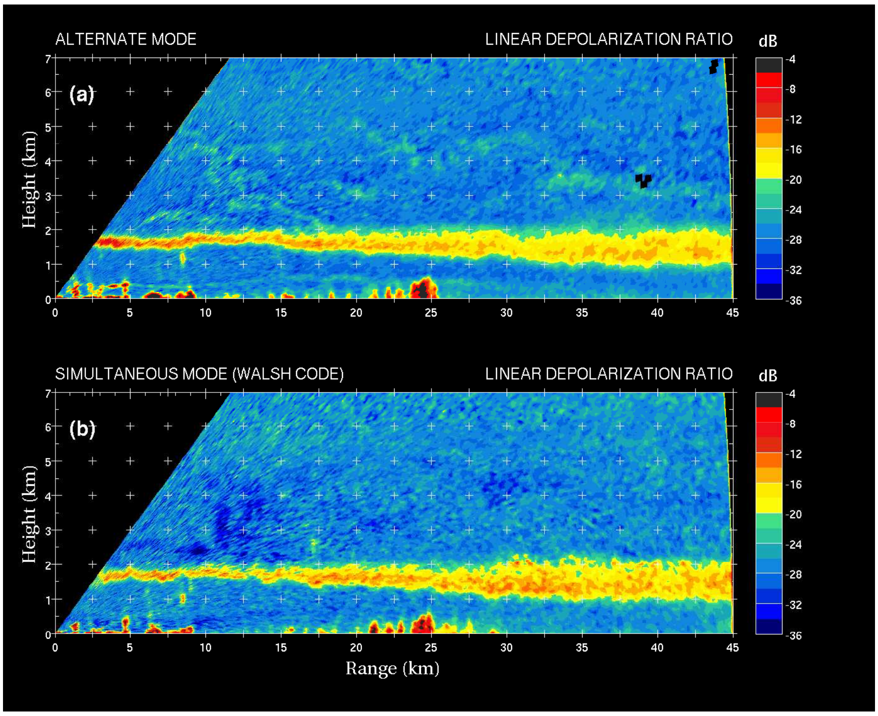

Figure 6: Comparison of LDR$_v$ measurements from alternate mode and simultaneous mode. Data collected from CSU-CHILL radar on 29 May, 2007 with alternate mode (20:34:00 UTC) and Walsh coded simultaneous mode (20:28:51 UTC) (a) Alternate mode (b) Simultaneous mode with Walsh code.

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