8.A3 MITIGATION OF CROSS-POLAR INTERFERENCE IN POLARIMETRIC WEATHER RADAR

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1 INTRODUCTION

Traditionally weather radar systems have been singularly polarized; i.e., with a preferred orientation for the transmitted energy. Typically this preferred orientation has been horizontal since rain drops are not spherical, but rather oblate spheroids. The horizontally oriented signals are more sensitive to the rain drops and hence scatter more energy. A notable exception is the network operated by the UK Met Office covering the United Kingdom uses vertical polarization. Interestingly, as studies of polarimetric weather radar data at C-band (wavelength ~5 cm) began, it was discovered that for many rainfall events Mie scattering effects are observed (Ryzhkov2005). The Mie scattering effects refer to resonant conditions between rain drop size and the amount of scatter. This phenomenon adds another dimension to the error in determining rainfall.

The first polarimetric weather radars transmitted pulses in a sequential fashion with high speed switches alternating between the horizontal and vertical channel on a pulse by pulse basis. The switches are/were relatively unreliable with a high failure rate. The past decade has seen the development of polarimetric radars that transmit energy in both polarizations simultaneously. These designs form the basis for the WSR-88D polarimetric upgrade and the polarimetric radars in the commercial and university arenas.

Polarimetry is a valuable resource for weather radar. It provides the additional information required to determine the type of precipitation (hydrometeors) present in the air as well as significantly improved rain rate estimates. In addition it has been shown that certain meteorological events such as tornadoes and lightning have very specific signatures in the polarimetric data fields (Ryzhkov2006, Hogan2002). In fact, polarimetric weather radars are the *only* radars that can identify whether a tornado has touched down.

The polarimetric moments are only as valuable as they are error free from cross-channel interference. The WSR-88D polarimetric test bed has a cross-polar isolation of 37 dB (Doviak, 2000). Similarly, the specification for the WSR-88D upgrade calls for isolation of 35 dB. Though respectable, the analysis by Wang (Wang, 2005) indicates that the cross polar isolation needs to be greater than 40 dB. Identifying cloud boundaries is one of the requirements presented in the Federal Research and Development Needs and Priorities for Phased Array Radar (OCFM2006) and requires cross-polar isolation on the order of 45 dB (Bringi, 2001). Thus, minimizing the cross-polar interference is critical to meeting the needs of the meteorological community and multiagency requirements.

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Currently deployed weather radar systems, for the most part, utilize parabolic reflector antenna designs. These designs provide a pencil beam and form a single hardware location for to focus on reducing cross-polar interference. Future systems under design such as the Multifunction Phased Array Radar (MPAR) are phased array antenna systems with multiple active elements. The beam is electronically steering, eliminating the current antenna positioner (pedestal) inherent in the current systems. However, crosstalk between polarimetric channels is traditionally greater in phased array systems than current parabolic antenna systems. As noted by the National Research Council (NRC, 2008), this is "a major challenge to the suitability of MPAR for weather surveillance". Hardware designs are progressing with a goal of reducing cross-polar interference (Zrnic, 2009).

In this paper, a signal processing technique is presented that can be implemented in current parabolic antenna systems as well as future phased array systems. The technique is based upon the work of Stagliano (2006) on extracting L_{DR} simultaneously with the other polarimetric measurables.

2 MEASUREMENT OF L_{DR} SIMULTANEOUS WITH THE OTHER POLARIMETRIC MEASURABLES

The linear depolarization ratio (L_{DR}) is the amount that a signal with a particular polarimetric orientations rotates to the complementary orientation upon scattering. For example, if the radar energy is transmitted with a horizontal polarization, a little bit of that energy is rotated into the vertical polarimetric orientation upon scattering. The ratio of the vertical signal power to the horizontal signal power on receive is the linear depolarization ratio, L_{DR},

$$L_{DR} = 10\log\left(\frac{S_{HV}}{S_{HH}}\right) \quad (1)$$

where S_{TR} represents the signal transmitted with orientation T and received with orientation R. The utility of measuring L_{DR} is in the phase space used for hydrometeor classification, L_{DR} has the greatest amount of separation from the other polarimetric variables. In this sense using L_{DR} allows less error in the classification algorithm. In addition, certain phenomena such as tornadoes and lightning have unique signatures in L_{DR}.

As described by Stagliano (2006) L_{DR} can be measured in simultaneous polarimetric weather radars at the same time as the other polarimetric variables. The technique works by separating the components of the received signals that were transmitted horizontally from those that were transmitted vertically. This can be accomplished by superimposing *orthogonal* modulations upon the signals in each channel upon transmit.

Two modulations, Ψ_H and Ψ_V, are considered orthogonal if when the inverse of a modulation is applied to itself returns unity, yet when applied to the other code returns zero. Mathematically, this is written,

$$\Psi_H^{-1}\Psi_H = \Psi_V^{-1}\Psi_V = 1 \quad (2)$$

and

$$\Psi_H^{-1}\Psi_V = \Psi_V^{-1}\Psi_H = 0\,. \quad (3)$$

Ignoring the error introduced by the cross-polar crosstalk, the transmitted signal can be written in terms of the horizontal and vertical components,

$$\vec{S}_T = H_T\hat{H} + V_T\hat{V}\,, \quad (4)$$

where

$$H_T = \Psi_H \text{ and } V_T = \Psi_V \quad (5)$$

assuming the transmit power in each channel is normalized to 1. The signal radiates out from the antenna, scatters off a target in the atmosphere. Upon scattering, the some of the horizontally polarized energy is rotated into the vertical polarization and similarly some of the transmitted vertically polarized energy is rotated into the horizontal polarization.

The signal in each receiver, horizontal and vertical, will have the following form,

$$H_R = \alpha H_T + \beta V_T\,, \quad (6)$$

and

$$V_R = \delta H_T + \gamma V_T\,, \quad (7)$$

where α, β, δ and γ are the relative power of the different components at the receiver.

Multiplying by the inverse function on each received components,

$$H_R^H = \Psi_H^{-1}H_R = \alpha\Psi_H^{-1}H_T + \beta\Psi_H^{-1}V_T = \alpha\,, \quad (8)$$

$$V_R^H = \Psi_H^{-1}V_R = \delta\Psi_H^{-1}H_T + \gamma\Psi_H^{-1}V_T = \delta\,, \quad (9)$$

$$H_R^V = \Psi_V^{-1}H_R = \alpha\Psi_V^{-1}H_T + \beta\Psi_V^{-1}V_T = \beta\,, \quad (10)$$

and

$$V_R^V = \Psi_V^{-1}V_R = \delta\Psi_V^{-1}H_T + \gamma\Psi_V^{-1}V_T = \gamma \quad (11)$$

are obtained. Thus, the entire polarimetric scattering matrix is determined and hence all of the polarimetric moments can be determined.

Chandrasekar (2007) demonstrated the efficacy of using orthogonal waveforms for extracting the all of the polarimetric measurables simultaneously. Chandrasekar et al. assessed the performance of the modulation techniques using random phase codes and a Walsh code. They were able to extract all of the polarimetric measurables simultaneously with the antenna cross-polar isolation as the limiting factor, demonstrating the viability of extracting L_{DR} simultaneously with the other polarimetric variables.

3 MITIGATING CROSS-POLAR INTERFERENCE

The cross-polar interference induced in the antenna (or other components) can be mitigated through the use of orthogonal waveforms, the same ones used to measure L_{DR} simultaneously. In the discussion of Section 2, the errors induced by the cross-polar interference were ignored. Including the channel cross-talk in the derivation gives,

$$H_T = \left(1-\varepsilon_H^T\right)\Psi_H + \varepsilon_V^T\Psi_V \quad (12)$$

and

$$V_T = \varepsilon_H^T\Psi_H + \left(1-\varepsilon_V^T\right)\Psi_V \quad (13)$$

where ε_H^T and ε_V^T are the cross-polarization coefficients associated with transmit antenna.

The signal in each receiver, horizontal and vertical, will have the following form,

$$H_R = \alpha H_T + \beta V_T + \varepsilon_H^R\left(\delta H_T + \gamma V_T\right) \quad (14)$$

and

$$V_R = \delta H_T + \gamma V_T + \varepsilon_V^R\left(\alpha H_T + \beta V_T\right) \quad (15)$$

where ε_H^R and ε_V^R are the cross-polarization coefficients associated with receive antenna and α, β, δ and γ are the relative powers of the different PSM components at the receiver. These terms are the ones to be determined error free.

Multiplying by the inverse function on each received signal in each channel,

$$H_R^H = \Psi_H^{-1}H_R = \left(1-\varepsilon_H^T\right)\alpha + \varepsilon_H^T\beta + \left(1-\varepsilon_H^T\right)\varepsilon_H^R\delta + \varepsilon_H^T\varepsilon_H^R\gamma \quad (16)$$

$$V_R^H = \Psi_H^{-1}V_R = \left(1-\varepsilon_H^T\right)\varepsilon_V^R\alpha + \varepsilon_H^T\varepsilon_V^R\beta + \left(1-\varepsilon_H^T\right)\delta + \varepsilon_H^T\gamma \quad (17)$$

$$H_R^V = \Psi_V^{-1}H_R = \varepsilon_V^T\alpha + \left(1-\varepsilon_V^T\right)\beta + \varepsilon_V^T\varepsilon_H^R\delta + \left(1-\varepsilon_V^T\right)\varepsilon_H^R\gamma \quad (18)$$

and

$$V_R^V = \Psi_V^{-1}V_R = \varepsilon_V^T\varepsilon_V^R\alpha + \left(1-\varepsilon_V^T\right)\varepsilon_V^R\beta + \varepsilon_V^T\delta + \left(1-\varepsilon_V^T\right)\gamma\,. \quad (19)$$

These four equations can be simplified into a simple matrix equation,

$$\vec{m} = \mathbf{E}\vec{x}\,, \quad (20)$$

where $\vec{m} = \left[H_R^H \quad V_R^H \quad H_R^V \quad V_R^V\right]^T$,

$$\mathbf{E} = \begin{bmatrix} 1-\varepsilon_H^T & \varepsilon_H^T & \left(1-\varepsilon_H^T\right)\varepsilon_H^R & \varepsilon_H^T\varepsilon_H^R \\ \left(1-\varepsilon_H^T\right)\varepsilon_V^R & \varepsilon_H^T\varepsilon_V^R & 1-\varepsilon_H^T & \varepsilon_H^T \\ \varepsilon_V^T & 1-\varepsilon_V^T & \varepsilon_V^T\varepsilon_H^R & \left(1-\varepsilon_V^T\right)\varepsilon_H^R \\ \varepsilon_V^T\varepsilon_V^R & \left(1-\varepsilon_V^T\right)\varepsilon_V^R & \varepsilon_V^T & 1-\varepsilon_V^T \end{bmatrix}, \text{ and}$$

$\vec{x} = \left[\alpha \quad \beta \quad \delta \quad \gamma\right]^T$. Solving Eqn. 20,

$$\vec{x} = \mathbf{E}^{-1}\vec{m}\,, \quad (21)$$

gives the noise limited polarimetric measurables that can be translated into the polarimetric moments. As the matrix, $\mathbf{E}$, is dependent only upon antenna parameters and is static, it and its inverse can be determined once prior to implementation.

4 CONCLUSION

Polarimetry is a valuable resource for weather radar. It provides the additional information necessary to determine the type of precipitation (hydrometeors) present in the air, significantly improves rain rate estimates, can identify lightning, nowcast lightning, and determine if a tornado has touched down. However, the polarimetric moments are only as valuable as they are error free from cross-channel interference.

This paper extended the use of orthogonal waveforms from not only recovering L_{DR} simultaneously with the other polarimetric moments, but also to mitigate interference between the polarimetric channels within the antenna.

Future work involves implementing the processing into a system using orthogonal waveforms and assessing its efficacy is eliminating the cross-polar interference.

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