Antenna pattern requirements for 3-PolD weather radar measurements

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(Dated: 17 July 2014)

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1. Introduction

The polarimetric measurement of weather targets is very demanding on terms of antenna parameters. In particular, it has been found that in order to have valid measurements of the reflectivity, Z, the differential reflectivity, Z_{DR}, and the copolar correlation coefficient, ρ_{hv}, their respective biases should be less than 1 dB, 0.1 dB and 0.005 [1], [2]. Achieving these biases requires well matched antenna patterns of the two antennas used for transmission/reception and very low cross-polar radiation. It has been demonstrated that if the simultaneous transmission simultaneous reception (STSR) algorithm is used, the cross-polar radiation is required to be significantly lower than if the alternate transmission simultaneous reception (ATSR) algorithm is used [1], [2]. Achieving this very low cross-polar radiation pattern requires a very careful design of the reflector antennas used in the mechanically scanned weather radars and it is challenging the development of phased array radars for weather surveillance that also need low cross-polar radiation for all scanning directions [3].

Considering the advantages that polarimetric measurements already provide and the benefits that the use of phased array radars could bring to the weather community, a search for algorithms and methods to obtain the accuracy required while integrating polarimetric capabilities on agile-beam phased arrays [4], [5] is on going.

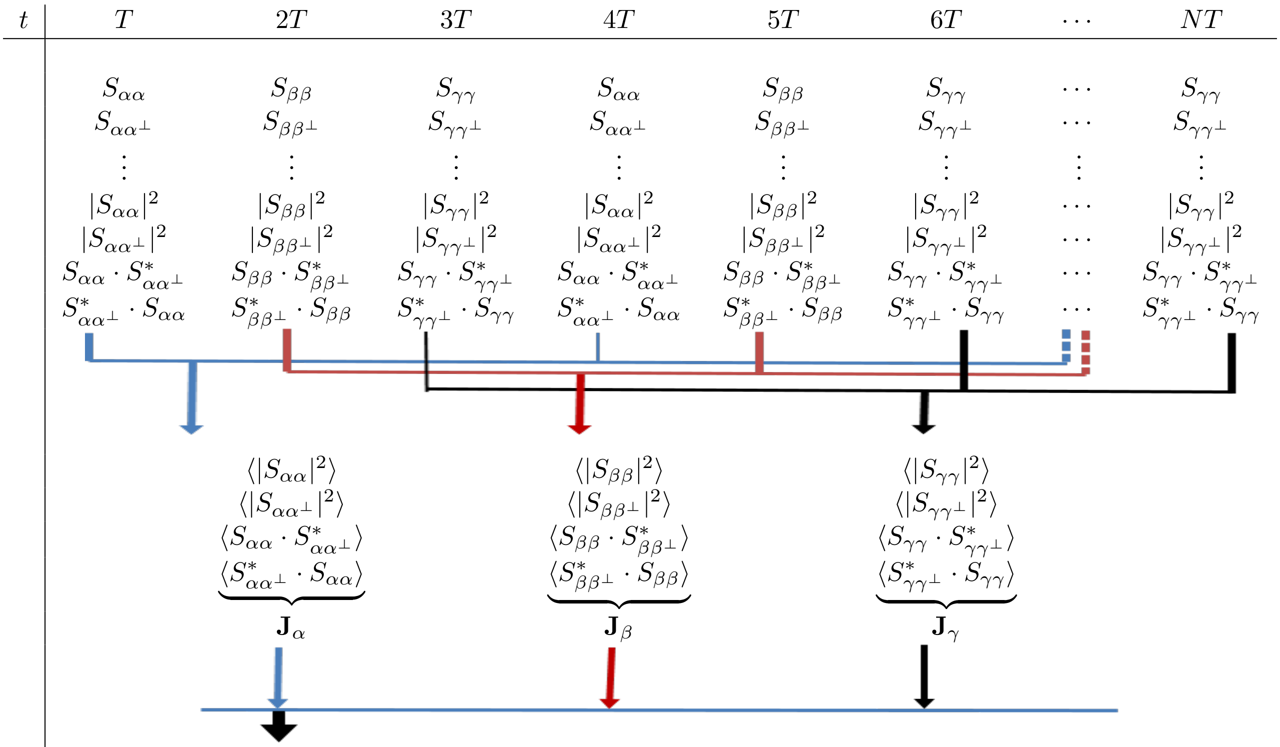
A fully polarimetric and Doppler measurement scheme (3-PolD) based on alternate transmission of three different polarizations while receiving with two differently polarized antennas has been proposed [6]. This measurement scheme provides the minimum variance unbiased linear estimates of the polarimetric covariance matrix elements from the available measurements. Its results compare well with those obtained with the STSR or ATSR method while not requiring any assumption on the Doppler or polarimetric characteristics of the target. Recently, it has been demonstrated that this method can be easily implemented on an agile-beam phased radar [7] without any loss in the accuracy of the polarimetric and Doppler estimates. The goodness of these results lead to the analysis of the cross-polar radiation effects on the 3-PolD measurements. Initial results have shown that antenna requirements for the cross-polar pattern can be relaxed with this measurement scheme. Besides, the flexibility in choosing the three different polarizations to transmit helps to meet the demanding cross-polar level requirements for all scanning directions.

The 3-POLD method will be briefly reviewed in the next section. Then, the effects of the cross-polar pattern on the polarimetric parameters will be discussed to end with the conclusions.

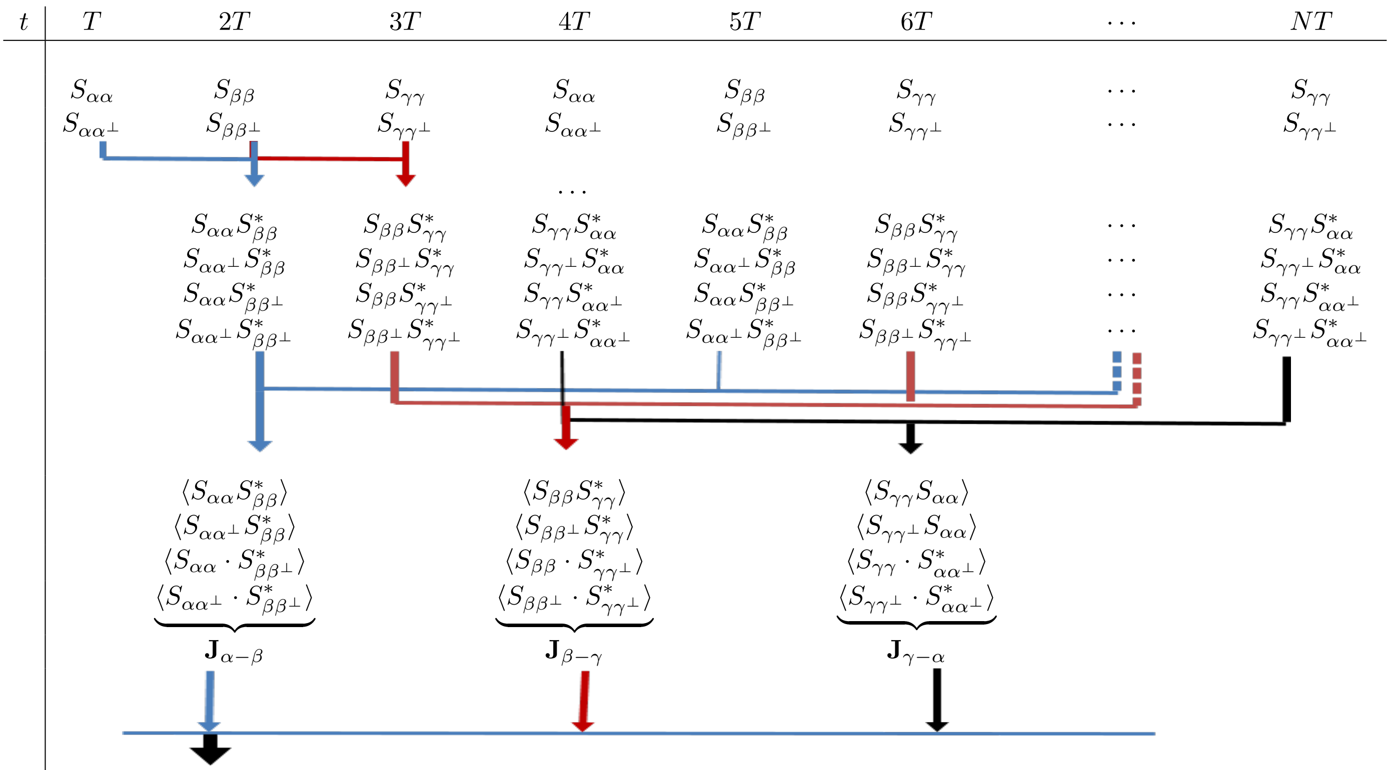
2. 3-POLD method review

The 3-POLD method considers sequential transmission of three different polarizations while simultaneously receiving their co- and cross-polar counterparts. This way, polarimetric and Doppler effects are decoupled. Linear least squares estimation is used to obtain the polarimetric parameters. Doppler parameters can be estimated with any of the methods proposed in the literature [8], [9].

Let's consider that the three alternately transmitted polarizations are $\hat{\alpha}$, $\hat{\beta}$ and $\hat{\gamma}$ and N pulses are transmitted. For each transmitted pulse two elements of the scattering matrix are obtained. If polarization $\hat{\alpha}$ is transmitted, $S_{\alpha\alpha}$ and $S_{\alpha\alpha^\perp}$ are measured ($\hat{\alpha}^\perp$ stands for the polarization orthogonal to $\hat{\alpha}$). Analogously, if polarizations $\hat{\beta}$ or $\hat{\gamma}$ are transmitted, $S_{\beta\beta}$ and $S_{\beta\beta^\perp}$ or $S_{\gamma\gamma}$ and $S_{\gamma\gamma^\perp}$ are measured ($\hat{\beta}^\perp$ and $\hat{\gamma}^\perp$ are the polarizations orthogonal to $\hat{\beta}$ and $\hat{\gamma}$). From these scattering matrix elements the corresponding coherency matrices can be obtained, then considering the realtionship between covariance matrices in different polarization bases and using linear least squares estimation the full polarimetric covariance matrix is obtained in the desired polarization basis. Similarly, scattering matrix elements at different time instants can be combined to finally obtain the temporal correlation function and the Doppler parameters of interest. It follows a schematic diagram of the procedure to get the covariance matrix and the Doppler parameters from the measurements, as just described.



$$\mathbf{J}_\alpha = \mathbf{P}\mathbf{M}_{HV-\alpha\alpha^\perp}\mathbf{C}_{HV}\mathbf{M}^{t*}_{HV-\alpha\alpha^\perp}\mathbf{P}^{t*}$$
$$\mathbf{J}_\beta = \mathbf{P}\mathbf{M}_{HV-\beta\beta^\perp}\mathbf{C}_{HV}\mathbf{M}^{t*}_{HV-\beta\beta^\perp}\mathbf{P}^{t*} \quad \rightarrow \text{Least Squares Estimator} \rightarrow \hat{C}_{HV}$$
$$\mathbf{J}_\gamma = \mathbf{P}\mathbf{M}_{HV-\gamma\gamma^\perp}\mathbf{C}_{HV}\mathbf{M}^{t*}_{HV-\gamma\gamma^\perp}\mathbf{P}^{t*}$$



$$\mathbf{J}_{\alpha-\beta} = \mathbf{P}\mathbf{M}_{HV-\alpha\alpha^\perp}\mathbf{C}_{HV}\mathbf{M}^{t*}_{HV-\beta\beta^\perp}\mathbf{P}^{t*}$$
$$\mathbf{J}_{\beta-\gamma} = \mathbf{P}\mathbf{M}_{HV-\beta\beta^\perp}\mathbf{C}_{HV}\mathbf{M}^{t*}_{HV-\gamma\gamma^\perp}\mathbf{P}^{t*} \quad \rightarrow \text{Least Squares Estimator} \rightarrow \widehat{C_{HV}\rho(T)} \rightarrow \hat{\rho}(T)$$
$$\mathbf{J}_{\gamma-\alpha} = \mathbf{P}\mathbf{M}_{HV-\gamma\gamma^\perp}\mathbf{C}_{HV}\mathbf{M}^{t*}_{HV-\alpha\alpha^\perp}\mathbf{P}^{t*}$$

where

$$\mathbf{P} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \tag{2.1}$$

and $\mathbf{M}_{HV-\alpha\alpha^\perp}$, $\mathbf{M}_{HV-\beta\beta^\perp}$ and $\mathbf{M}_{HV-\gamma\gamma^\perp}$ are unitary matrices to change the covariance matrix from HV-basis to $\alpha\alpha^\perp$-basis, $\beta\beta^\perp$-basis and $\gamma\gamma^\perp$-basis respectively.

3. Cross-polar radiation pattern effects on 3-PolD measurements

To analyse the bias in the polarimetric parameters of interest that cross-polar radiation causes when using the 3-PolD method, two ideal cross-polar radiation patterns, representative of different real situations, will be considered [2]. The same co-polar pattern is assumed for both cross-polar patterns. Two identical but orthogonally polarized radiating elements are considered to generate alternately the three polarizations with the following assumptions: their co-polar and cross-polar patterns are equal, there might be a phase shift between the co-polar fields radiated by each element, co- and cross-polar fields may also be phase shifted and co-polar maximum is much higher than cross-polar one [2].

3.1. Co-polar pattern

The co-polar antenna gain is assumed to be Gaussian:

$$g_c(\theta,\phi) = g_c e^{-4\ln(2)\frac{\theta^2}{\theta_c^2}} \tag{3.1}$$

with g_c the maximum gain and θ_c, the 3 dB beam width. A 45.6 dB gain and a 1^o of half power beamwidth have been assumed in results presented in figures 3 to 10.

3.2. Coaxial cross-polar pattern

The coaxial cross-polar pattern presents a main lobe coincident with the co-polar pattern main lobe. It is also assumed as Gaussian,

$$g_x(\theta,\phi) = g_x e^{-4\ln(2)\frac{\theta^2}{\theta_x^2}} \tag{3.2}$$

with g_x the maximum gain and θ_x, the 3 dB beam width.

3.3. Four-lobe cross-polar pattern

This pattern presents a zero in the co-polar main lobe axis and four lobes equally spaced in azimuth. Each lobe follows a Gaussian pattern as:

$$g_x(\theta,\phi) = g_x e^{-4\ln(2)\frac{(\theta-\theta_p)^2+(\phi-\phi_p)^2}{\theta_x^2}} \tag{3.3}$$

with g_x the maximum gain of each lobe, θ_x, the 3 dB beam width, θ_p the angle between co-polar lobe axis and cross-polar lobes axis and ϕ_p the azimuth orientation angle.

Cross-polar pattern parameters, g_x and θ_x, are determined in terms of the cross- to co-polar peak radiation pattern, XPL, considered:

$$XPL(dB) = 10\log_{10}\frac{g_x}{g_c} \tag{3.4}$$

Knowing the antennas' radiation patterns, the biases of the polarimetric parameters' estimates can be calculated [2], [10]. These biases have been calculated for the reflectivity (Z_h), the differential reflectivity (Z_{dr}), the copolar correlation coefficient (ρ_{hv}) and the differential propagation phase shift (K_{dp}) for different types of hydrometeors.

For a given class of hydrometeors and given antennas' radiation patterns, the bias of any parameter depends on the propagation phase shift and the phase shifts between co- and cross- polar fields [1], [2]. In the results that follow the maximum value of the bias is shown, that is, the error bound for each parameter due to cross-polar radiation.

Biases are shown as a function of the XPL for the two cross-polar patterns defined. Absolute bias of reflectivity and differential reflectivity are shown in dB, relative bias of copolar correlation and differential propagation phase shift are shown as a percentage.

The worst results are obtained, as it could be expected, for the coaxial cross-polar pattern, though even for a XPL as high as -10 dB, all parameters are measured with the desired accuracy. These results are at least as good as those obtained with

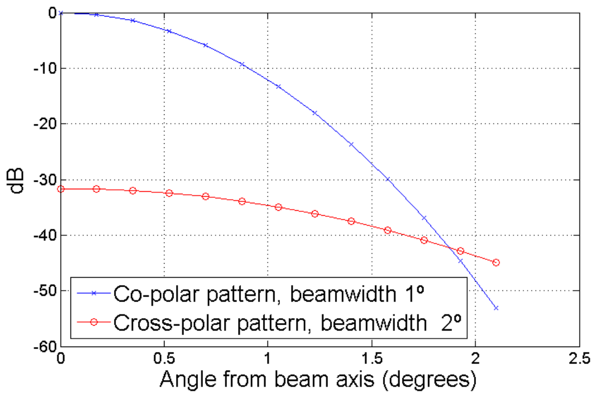


Figure 1: Co- and coaxial cross-polar patterns

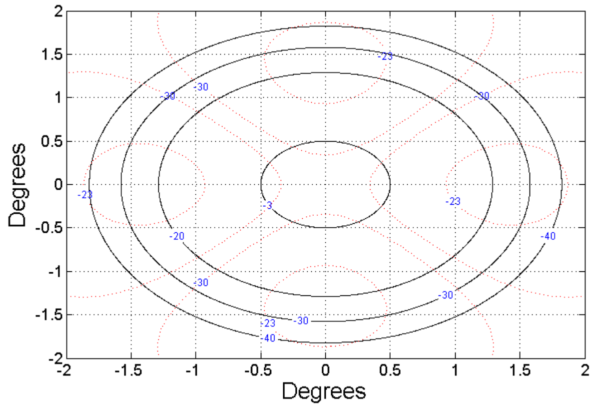


Figure 2: Co- (black) and four-lobe cross-polar (red) pattern contour.

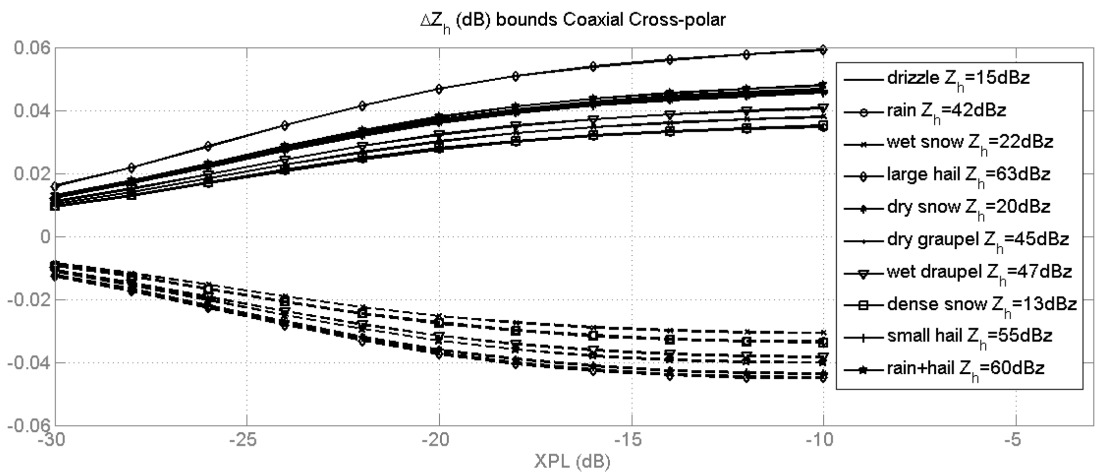


Figure 3: Z_h bias. Coaxial cross-polar pattern

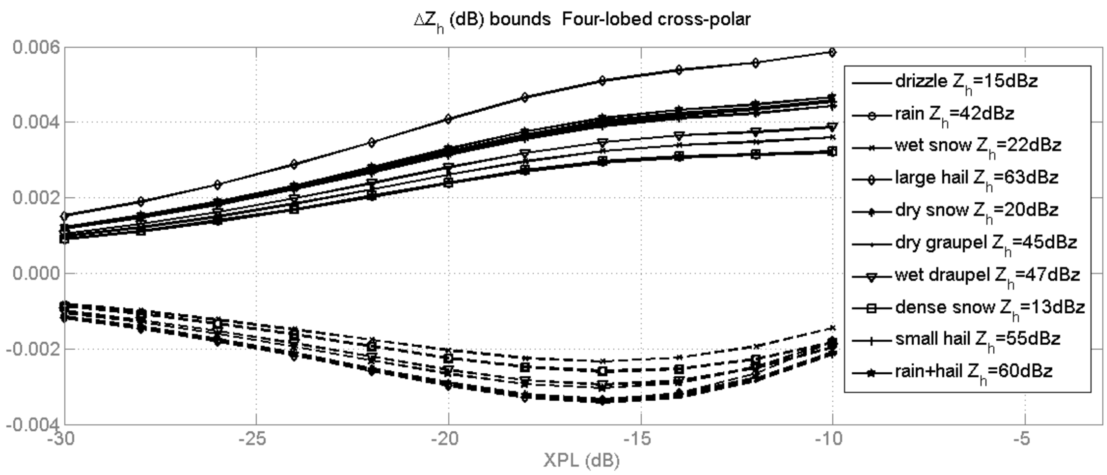


Figure 4: Z_h bias. Four-lobe cross-polar pattern

the ATSR method, and clearly better than the results obtained with the STSR method, which, for example, to keep the bias of the differential reflectivity below 0.1 dB requires a XPL below -45 dB for the coaxial cross-polar pattern and of -21 dB if the four-lobe cross-polar pattern is considered [2].

4. Conclusions

The bias due to cross-polar radiation when the 3-PolD method is considered to perform polarimetric Doppler measurements has been calculated for two different cross-polar patterns, that could be considered extreme idealized cases. Most real cross-polar patterns are a combination of these. Results show that the 3-PolD method provides measurements with the required accuracy without imposing too stringent requirements on the antennas. In this regard, its behavior compares well with the ATSR method, and clearly overcome the STSR performance. Previously, it has been shown [6] that the 3-PolD method

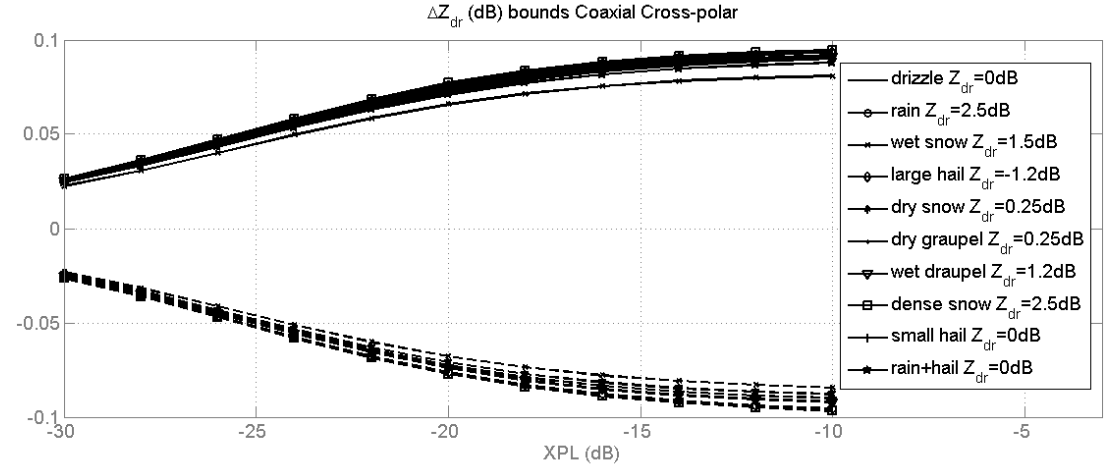


Figure 5: Z_{dr} bias. Coaxial cross-polar pattern

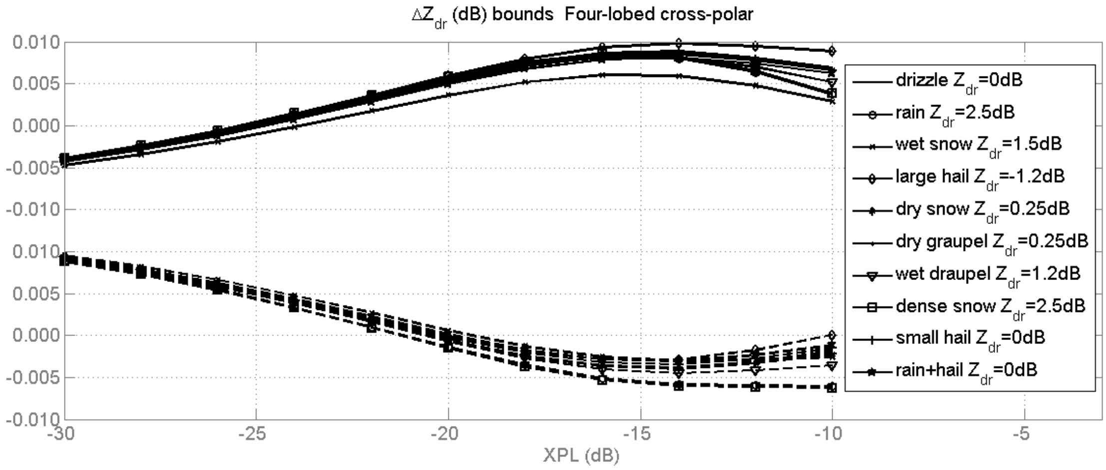


Figure 6: Z_{dr} bias. Four-lobe cross-polar pattern

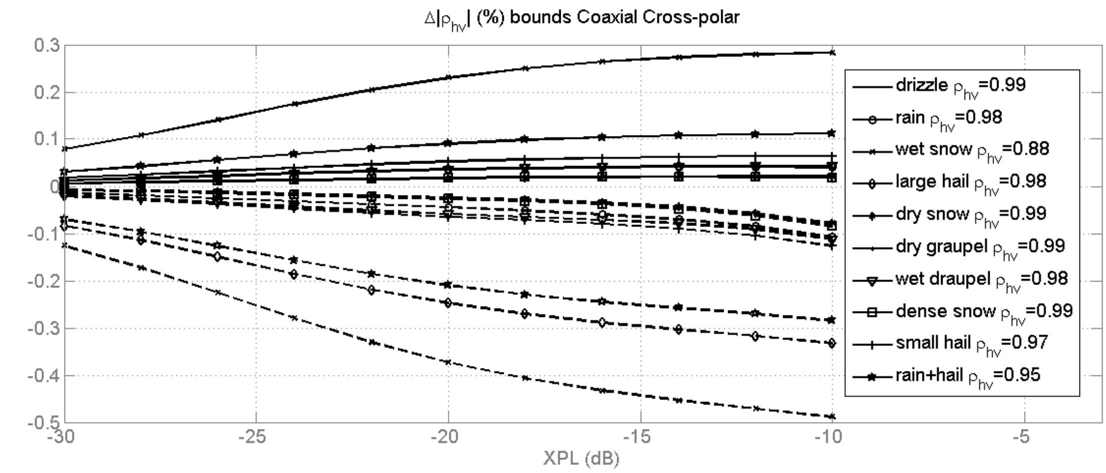


Figure 7: ρ_{HV} bias. Coaxial cross-polar pattern

provides minimum variance unbiased linear estimates of the polarimetric covariance matrix and Doppler parameters within the Doppler bandwidth determined by the pulse repetition time, T. Because it decouples polarimetric and Doppler parameters it does not require to make any assumption regarding the temporal correlation function. Besides, it has been shown in [7] how the 3-PolD method, due to its nature, it is not affected by the biases due to the change of transmitting and receiving polarizations with the pointing direction that occurs when considering an electronically scanned planar array [7]. These properties make the 3-PolD method a good candidate, that may be considered, for the future weather phased array radar systems.

Acknowledgement

This research is partially supported by the European Regional Development Fund (ERDF) and the Galician Regional Government under project CN 2012/260 "Consolidation of Research Units: AtlantTIC" and the Spanish State Secretary for Research

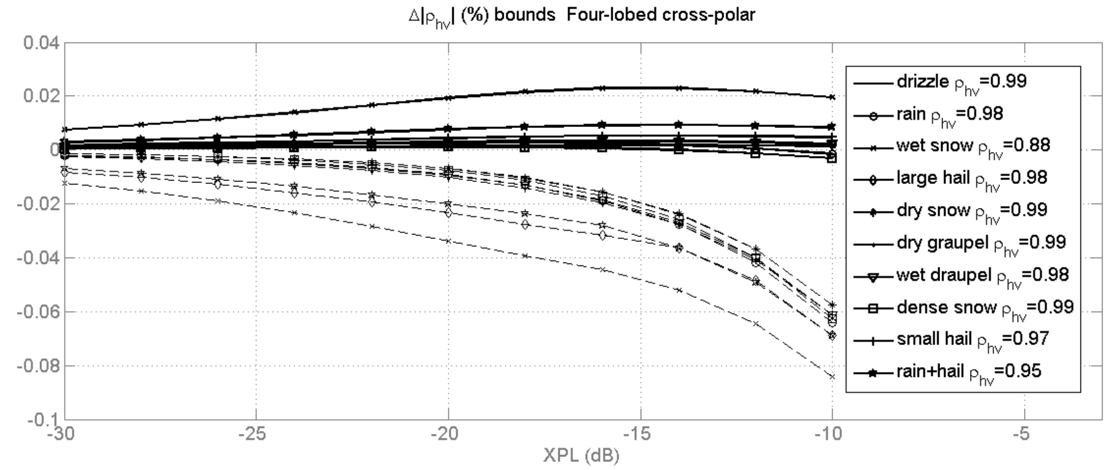


Figure 8: ρ_{HV} bias. Four-lobe cross-polar pattern

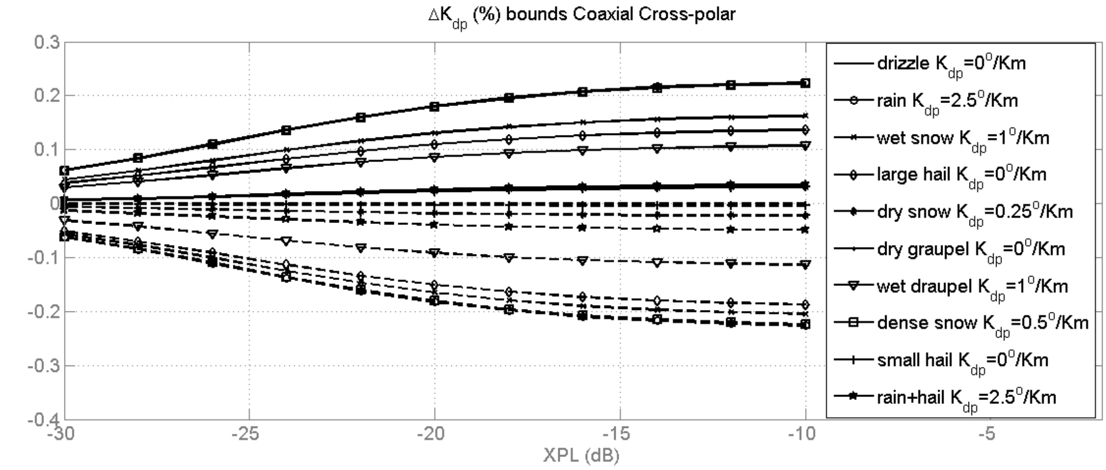


Figure 9: K_{dp} bias. Coaxial cross-polar pattern

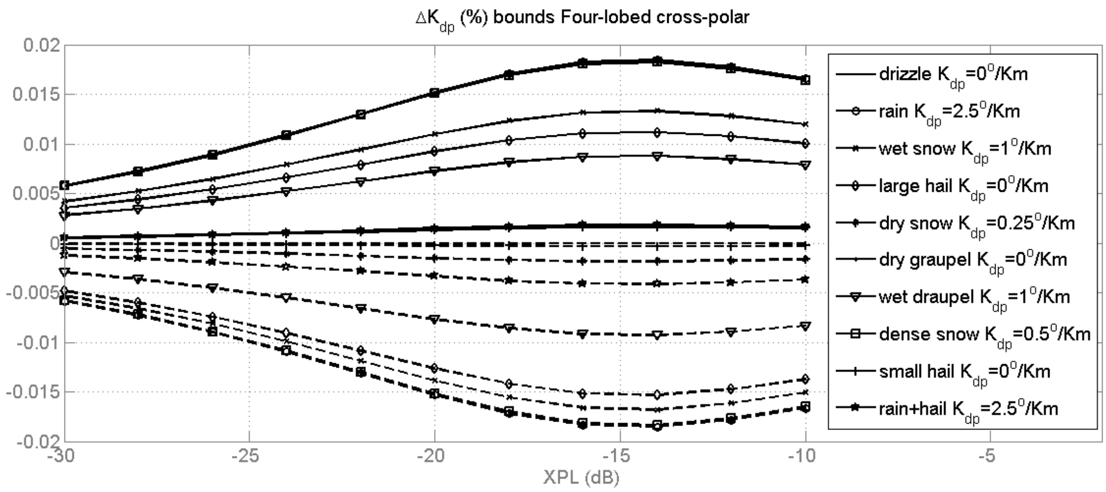


Figure 10: K_{dp} bias. Four-lobe cross-polar pattern

under project TEC2011-28789-C02-02.

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