Antenna polarization errors and biases in polarimetric variables for simultaneous horizontal and vertical transmit radar

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8 July 2010

1. Introduction

It is now well accepted that dual polarization weather radar data can significantly improve the quantitative as well as qualitative description of precipitation. Mainly for economic reasons, the simultaneous transmission and reception of H (horizontal) and V (vertical) polarized waves (called SHV mode) has become a very popular way to achieve dual polarization. The viability of the SHV technique is base on 1) non-zero mean canting angle of the propagation medium, and 2) negligible antenna polarization errors. Both (1) and (2) will cause cross-coupling between the H and V channels which leads to measurement biases.

We show how transmit differential phase affects $Z_{dr}$ (differential reflectivity) bias and how little differential propagation phase need accumulated before significant $Z_{dr}$ biases occur. Wang and Chandrasekar (2006) concluded that system isolation between the the H and V channels must be greater than 44 dB in order to insure that the $Z_{dr}$ bias is with 0.2 dB for worst case errors. We show that requirement can be relaxed to about 41 dB at least for the type of antenna errors seen for S-Pol, NCAR’s S-band polarimetric radar. Experimental data from S-Pol are used to illustrate the theory. Recently, S-Pol collected data in fast alternating H and V mode (referred to as FHV mode) quickly followed by data collected in simultaneous H and V transmit mode. These data clearly illustrate the effects of antenna polarization errors.

2. Radar scattering model

The radar scattering model used is described in Hubbert and Bringi (2003). The received voltages can be modeled as

$$\begin{bmatrix} V_{h}^r \\ V_{v}^r \end{bmatrix} = \Upsilon^T R(-\theta) P^T S P R(\theta) \Upsilon \begin{bmatrix} V_{h}^i \\ V_{v}^i \end{bmatrix}$$

(1)

where $V_{h,v}^i$ are the complex voltages delivered to the antenna, $\Upsilon$ is the antenna error matrix, $R$ is the Cartesian rotation matrix, $P$ is the propagation matrix, $S$ is the backscatter matrix and $T$ denotes transpose. Upon expansion of the matrix multiplications, covariances of the received voltages can be calculated. The propagation scattering is coherent and the antenna errors are considered constant across the antenna beam. The backscatter covariances (i.e., integration over the ensemble of scatterers in the backscatter volume) are calculated using the T-matrix method.

Antenna errors are quantified in the model by the complex numbers $\xi_h$ and $\xi_v$ (Hubbert et al. 2010a)

$$\Upsilon = \begin{bmatrix} i_h & \xi_v \\ \xi_h & i_v \end{bmatrix}$$

(2)

with constraints $i_h^2 + |\xi_h|^2 = i_v^2 + |\xi_v|^2 = 1$ where $i_h$, $i_v$ are real. These errors can be equivalently defined by the tilt and ellipticity angles, i.e., $\alpha_{h,v}$ and $\epsilon_{h,v}$, respectively, of the polarization ellipse. Representing the antenna polarization errors in terms of the the tilt and ellipticity angles provides insight as to the character of the antenna errors. A more detailed description of the radar scattering model can be found in Hubbert et al. (2010a); Hubbert and Bringi (2003).

The model is used to illustrate the biases of SHV $Z_{dr}$ caused by 1) the mean canting angle of the propagation medium and 2) antenna polarizations errors. Shown in Fig. 1 is SHV $Z_{dr}$ as a function of principal plane $\phi_{dp}$ with the mean canting angle of the propagation medium as a parameter. The left hand panel is for linear slant 45° polarization (i.e., $V_{h}^i = V_{v}^i$) and the right hand panel is for circular transmit polarization (i.e., $V_{h}^i = e^{j(\pi/2)} V_{v}^i$). If the transmit polarization is circular, only a few degrees of principal plane $\phi_{dp}$ need accumulate to cause several tenths of a dB bias in $Z_{dr}$. 
3. **SHV Z\textsubscript{dr} as a function of \textit{LDR} system limit**

The antenna polarization error terms appear as $\xi_h + \xi_v$ in the expression for \textit{LDR} system limit and SHV $Z_{\text{dr}}$ in drizzle. Thus, the \textit{LDR} system limit for a radar can be related to the SHV $Z_{\text{dr}}$ bias as a function of $\phi_{dp}$, with differential transmit phase as a parameter. Based on the antenna errors for S-Pol, the antenna errors are modeled as orthogonal ellipticity angles with no tilt angle errors. This is shown in Fig. 2 for (a) slant 45° linear transmit polarization (i.e., $E_t^h = E_t^v$) and (b) circular transmit polarization. The shown $\epsilon$ denotes the sign of the H polarization ellipticity angle. Note how not only the shape of bias curves changes but also the maximum $Z_{\text{dr}}$ bias increases significantly for circular transmit polarization. The model shows that the most stringent crosspolar isolation criteria results for the circular polarization transmit condition. As can be seen, if SHV $Z_{\text{dr}}$ bias is to be kept under 0.2 dB, the \textit{LDR} system limit needs to be about -40 dB. Practically, if one of the circular transmit bias curves characterized a radar, the $Z_{\text{dr}}$ bias at $\phi_{dp} = 0^\circ$ would likely be detected by the user and a $Z_{\text{dr}}$ offset correction factor would be used. Then, the maximum $Z_{\text{dr}}$ bias would occur for $\phi_{dp} = 180^\circ$ instead of at $\phi_{dp} = 0^\circ$.

4. **S-Pol experimental SHV data**

During May and June of 2008, S-Pol was deployed in Southern Taiwan for the field experiment TiMREX (Terrain-influenced Monsoon Rainfall Experiment). S-Pol was operated in the FHV (fast alternating H and V polarization) transmit mode for the majority of the project (normal operation mode). However, limited data were collected in the SHV (simultaneous H and V transmit) mode interleaved with the FHV data (Hubbert et al. 2010b). Thus, SHV and FHV data that were gathered only minutes apart can be compared. Two cases are examined: 1) 8.6° elevation data which demonstrate $Z_{\text{dr}}$ bias likely caused by non zero-mean canting angle of the propagation medium, and 2) 2.0° elevation data which demonstrates $Z_{\text{dr}}$ bias in rain caused by antenna polarization errors. The S-Pol data presented here were gathered on 2 June 2008.

Figure 3 A, B and C show S-Pol FHV mode $Z$ (reflectivity), $Z_{\text{dr}}$ and $\phi_{dp}$ gathered at 6:19:36 UTC at 8.6° elevation. Figure 3D, E and F show SHV $Z$, $Z_{\text{dr}}$ and $\phi_{dp}$ gathered at 6:13:59 UTC at 8.6° elevation. A line of convective cells lies to the southeast of the radar with trailing stratiform rain to the west. Storm cells were moving west to east. At about 35 km range, high and noisy $Z_{\text{dr}}$ values mark the brightband. Note the radial stripes of $Z_{\text{dr}}$ in the SHV mode data beyond the brightband (Fig. 3E). No $Z_{\text{dr}}$ radial stripes are evident in the FHV $Z_{\text{dr}}$ data of Fig. 3B. The $Z_{\text{dr}}$ striping in Fig. 3E is likely due to non zero-mean canting angle of the ice particles in the propagation path, in agreement with Ryzhkov and Zrnić (2007). Figure 3C and F show that FHV and SHV $\phi_{dp}$ are similar. This is expected from the model even though significant differences between SHV and FHV $K_{dp}$ (specific differential phase) can occur for large non zero-mean canting angle of the precipitation medium coupled with significant increase of $\phi_{dp}$. Both plots show similar large $\phi_{dp}$ increase versus range with a maximum increase of about 30° along the 178° radial. Such a large
Figure 2: SHV mode $Z_{dr}$ bias as a function of principal plane $\phi_{dp}$ with LDR system limit as a parameter. The antenna polarization errors are assumed to be orthogonal ellipticity angles. The sign of the $H$ ellipticity angle is given in each quadrant. (a) The transmit polarization is 45° linear, i.e., $E_t^h = E_t^v$. The curves all mimic a sine wave shape. (b) The transmit polarization is circular. The curves are symmetric about the vertical line through 180°.

increase of $\phi_{dp}$ in the ice phase of storms indicates that there are highly aligned ice crystals, which could be due to electrification. It is difficult to precisely quantify the mechanisms that cause the radial SHV $Z_{dr}$ biases evident in Fig. 3E without having in-situ verification of the precipitation particle size and shape. These figures do indicate that there is significant alignment of the ice particles and the radar model from Part I shows that such radial SHV $Z_{dr}$ bias stripes can be caused by such particles if they possess a non-zero mean canting angle.

Less well known is the possible SHV $Z_{dr}$ bias in rain due to antenna polarization errors. As shown in Fig. 2 an LDR system limit of -30 dB to -35 dB indicates an SHV $Z_{dr}$ bias of up to about 0.5 dB maximum can occur when $\phi_{dp}$ increases significantly. In this section we present experimental data that demonstrate the existence of this SHV $Z_{dr}$ bias in rain.

Figure 4A, B and C show S-Pol FHV mode $Z$, $Z_{dr}$ and $\phi_{dp}$ gathered at 6:17:06 UTC at 2.0° elevation. Figure 4D and E show SHV $Z$ and $Z_{dr}$ gathered at 6:11:28 UTC at 2.0° elevation. There is no $Z_{dr}$ striping evident in the SHV data of Fig. 4E since the elevation angle is low and most of the data are in rain which should have zero mean canting angle. The SHV and FHV $Z_{dr}$ data appear fairly comparable but in fact there is a bias in the SHV data. To show this, we employ the self-consistency $Z_{cal}$ calibration technique of Vivekanandan et al. (2003). The technique is based on the relationship of $Z$, $Z_{dr}$ and $\phi_{dp}$ in rain. Assuming the typical range of rain drop size and shape equilibrium distributions, $\phi_{dp}$ can be estimated from measured $Z$ and $Z_{dr}$. This estimated $\phi_{dp}$ ($\phi_{dp}^m$) is compared to the measured $\phi_{dp}$ ($\phi_{dp}^m$). A scatter plot is generated and a straight line fit is calculated. If the calculated mean line differs from the 1-to-1 line, this indicates a reflectivity bias. The technique assumes that $Z_{dr}$ is well-calibrated (S-Pol $Z_{dr}$ is well-calibrated via vertical pointing data in light rain).

Figure 5 shown calculated $\phi_{dp}$ versus measured $\phi_{dp}$ for the SHV data. The scatter is rather tight about the 1-to-1 line for $\phi_{dp} < 50^\circ$ but for $\phi_{dp} > 70^\circ$, the computed $\phi_{dp}$ are biased low. We believe that this is due to biased SHV $Z_{dr}$ caused by antenna polarization errors.

To further illustrate this SHV $Z_{dr}$ bias, $Z_{dr}$ is averaged under the constraint 20 dBZ < $Z$ < 25 dBZ for different ranges of $\phi_{dp}$. The $\phi_{dp}$ ranges reflect the different bias characteristics at different $\phi_{dp}$ values shown in Fig. 5. Therefore, the data are partitioned into three categories: 1) 20° < $\phi_{dp}$ < 40°, 2) 40° < $\phi_{dp}$ < 70°, and 3) 70° < $\phi_{dp}$ < 100°. The results from such analysis show that for low $\phi_{dp}$ the SHV and FHV $Z_{dr}$ values are approximately equal. For 40° < $\phi_{dp}$ < 70°, they differ by 0.11 dB and for 70° < $\phi_{dp}$ < 100° they differ by 0.27 dB. This increasing difference between FHV and SHV $Z_{dr}$ as a function of $\phi_{dp}$ is consistent with the $Z_{dr}$ bias predicted for antenna errors of radar systems with LDR limit in the -30 dB to -35 dB range. Note that the $Z_{dr}$ are not corrected for differential attenuation, hence measured $Z_{dr}$ decreases with increasing $\phi_{dp}$.

In Hubbert et al. (2010a) S-Pol antenna errors were estimated based on sun calibrations and LDR system limit
Figure 3: PPI data for 8.6 deg elevation. FHV data are in the left hand panels include: (A) reflectivity (Z), (B) $Z_{dr}$, and (C) $\phi_{dp}$. The corresponding SHV data are in the right hand panels (D, E, and F, respectively). The data were gathered by S-Pol on 2 June 2008 at 06:19:36 UTC during the Field Campaign TiMREX in southern Taiwan. Range rings are in 15 km increments.
Figure 4: PPI data for 2.0 deg elevation. FHV data are in the left hand panels include: (A) reflectivity ($Z$), (B) $Z_{dr}$, and (C) $\phi_{dp}$. The corresponding SHV $Z$ and $Z_{dr}$ data are in the right hand panels (D, and E, respectively). The data were gathered by S-Pol on 2 June 2008 at 06:16:06 UTC during the Field Campaign TiMREX in southern Taiwan. Range rings are in 15 km increments.
Figure 5: Scatter plot of calculated $\phi_{dp}$ (from measured $Z$ and $Z_{dr}$) versus measured $\phi_{dp}$ from TiMREX SHV data. Left: corresponding to Figs. 4D and E. Data above approximately 50° are biased low (consistently fall below the one-to-one line). This is a manifestation of the $Z_{dr}$ bias caused by antenna polarization errors. Right: $Z_{dr}$ is corrected as a function of measured $\phi_{dp}$.

measurements. These estimated antenna errors were used in the radar scattering model to predict SHV $Z_{dr}$ bias. These predicted $Z_{dr}$ biases are then used to correct the S-Pol experimental SHV data above. The self consistency technique is then again applied to the corrected data and the result is shown in Fig. 5, right hand panel. As can be seen the data are now better clustered around the one-to-one line as compared to the uncorrected data of Fig. 5 (left hand panel).

5. Conclusions

Simultaneous transmission of H and V polarized waves (termed SHV mode) is now a popular way to construct dual-polarization radar systems largely because of lower cost and technical simplicity: an expensive, fast, high-power polarization switch is avoided. This paper has shown that data quality issues will likely limit the cost-benefit of the SHV technique unless antenna polarization errors can be reduced so that the crosspolar isolation is better than 40 dB, a figure of merit difficult to achieve for center-fed parabolic reflector antennas.

Acknowledgment This research was supported in part by the ROC (Radar Operations Center) of Norman OK. The National Center for Atmospheric Research is sponsored by the National Science Foundation. Any opinions, findings and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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