P13.22 Evaluation of two integrated techniques to estimate the rainfall rates from polarimetric radar measurements and extensive monitoring of azimuth-dependent $Z_{DR}$ and $\phi_{DP}$ biases

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1. Introduction

Polarimetric radars are currently being introduced into operational networks. In addition to the three Doppler momentum, a polarimetric radar simultaneously transmitting H and V provides the differential reflectivity ($Z_{DR}=Z_H-Z_V$, expressed in dB), the copolar-correlation coefficient ($\rho_{HV}$, no units) and the differential phase ($\phi_{DP}$, expressed in degrees). $\rho_{HV}$, the amplitude of the complex correlation between the time series at horizontal and vertical polarization, is extremely powerful in distinguishing rain, the bright band, hail and non meteorological echoes. Because of the increasing oblateness of rain drops with their increasing equivalent diameter (Briggs and Chandrasekar 2001), $Z_{DR}$ is a good estimate of the mean drop diameter. $\phi_{DP}$, the phase difference between the H and the V wave ($\phi_H-\phi_V$), is an excellent indicator of attenuation and can be used to correct for it (Gourley et al. 2007a). Its range derivative, $K_{DP}$, is related to rainfall rate and is almost immune to drop size distribution (DSD) variations. Many studies have demonstrated that polarimetric rain rate estimators outperform conventional ones, provided that all variables (essentially $Z_H$ and $Z_{DR}$) are well calibrated. The most frequent approach extends the conventional R(Z) relationship by expressing rainfall rate $R$ (in mm h$^{-1}$) as a function of polarimetric radar parameters.

Three types of relationships have been proposed: $R(Z, Z_{DR})$, $R(K_{DP}, Z_{DR})$ and $R(K_{DP})$ (Gorgucci et al. 2001; Ryzhkov et al. 2005). These findings have been explored in the JPOLE experiment (Ryzhkov et al. 2005) during which various polarimetric relationships applied to the prototype polarimetric WSR-88D KOUN S-Band radar were compared. The authors concluded that most polarimetric algorithms outperform conventional R(Z) at distance less than 125 km and that the best results are obtained with a synthetic $R(Z, K_{DP}, Z_{DR})$ algorithm.

One of the problems with pixel-based polarimetric rain rate estimation is that the polarimetric variables are noisy, especially $K_{DP}$, which is the range derivative of a noisy phase profile (typical noise on $\phi_{DP}$ is 3°). The required precision of $Z_{DR}$ and $K_{DP}$ cannot be obtained at the pixel scale with the pulse durations, antenna rotation rates and beamwidths typically used by operational radars. For that reason, some authors have proposed so-called ‘integrated’ algorithms in order to retrieve the characteristics of the drop size distribution (DSD) over a sub-domain of the radar image in a more robust manner. Once the parameters of the DSD are obtained, the reflectivity value of each individual pixel is converted into rainfall rate using the appropriate Z-R relationship. This is the principle of the ‘integrated ZZDR’ algorithm proposed for moderate rainfall rates by Illingworth and Thompson (2005). It is also the philosophy of the ZPHI algorithm (Testud et al. 2000) and of the Hogan (2007) algorithm. ZPHI, which simultaneously corrects for attenuation and DSD fluctuations, has been successfully tested and compared to a conventional $R(K_{DP})$ approach (Le Bouar et al. 2001).

In this paper, we present the results of a comparison between ZPHI and ZZDR performed using one year of data collected by the French operational polarimetric C-band Trappes radar (Gourley et al. 2006). The performances of the two algorithms are assessed for hourly time steps against a dense rain gauge network. The conventional ($Z=282R_{0.6}$) estimator is taken as the benchmark.

Because polarimetric algorithms are so much dependent upon the calibration of polarimetric variables, significant efforts have been devoted lately at Météo France on the definition and real-time production of monitoring indicators. Those monitoring indicators are described and illustrated in Appendix.

2. Description of the two integrated polarimetric estimators

The ZPHI algorithm has been described in several papers (Testud et al. 2000; Le Bouar et al. 2001). The starting point is a set of $N_b$-normalized relationships between $Z_H$ (intrinsic horizontal reflectivity in mm$^2$ m$^{-3}$), specific attenuation at horizontal polarization ($A_H$ in dB km$^{-1}$), specific differential phase ($K_{DP}$ in deg km$^{-1}$) and rain rate ($R$ in mm h$^{-1}$):

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corresponds to the climatological value of log corrected for attenuation, to rainfall, this formula used to convert the horizontal, reflectivity, possibly with N noise on the polarimetric variables. As it only uses Z precipitation. The partition is achieved on the basis on standards. The “constant N rain rates according to (northern) European segment exceeds significantly the typical noise on the following formula (still assuming Hogan (2007), no continuity on N dependence upon the calibration of horizontal rotation), then a default ZR relationship, Z=282R 0

polynomial in log ςH (especially K azimuth, the constraint on the required minimum ΔDP = 6 degrees phase shift is required for the algorithm to be triggered. Even though any estimated N₀ value can, to a certain extent, be extrapolated in range and / or azimuth, the constraint on the required minimum ΔDP implies that the algorithm is triggered, at C-band, for rain rates above 3 – 4 mm h⁻¹, i.e. moderate to heavy rain rates according to (northern) European standards. The “constant N₀ constraint” can be enforced by separating stratiform and convective precipitation. The partition is achieved on the basis on the rain rate retrieved without performing any partition. In conclusion, the ZPHI is well suited to handle the noise on the polarimetric variables. As it only uses ZH and ϕDP and not ZDR, the estimated rain rates are only dependent upon the calibration of horizontal reflectivity. The drawbacks are that the algorithm is only triggered (at C-band) for rain rates above 3 – 4 mm h⁻¹ and that, unlike the approach proposed by Hogan (2007), no continuity on N₀ is imposed along the azimuth. When the algorithm is not triggered (for cases when there is less than 6° differential phase rotation), then a default ZR relationship, Z=282R⁻¹.⁶⁶ is used to convert the horizontal, reflectivity, possibly corrected for attenuation, to rainfall, this formula corresponds to the climatological value of log_{10}(N₀) of 8.3 obtained from a long time series of disdrometer data by Testud (2003).

The integrated ZZDR algorithm (Illingworth and Thompson 2005) starts from the following relationship between ZH and ZDR:

\[ Z_{\text{dr}}(\text{dBZ}) = P(\log_{10}(Z_{\text{dr}}(\text{dB}))) + T \]

where ZDR is in dB, ZH in dBZ, and P is a third-order polynomial in \log_{10}(ZDR) obtained using T-matrix simulations at C-band for a normalized gamma DSD with μ=5 (Bringi and Chandrasekar 2001).

\[ P(x) = -3.1317x^3 + 6.4566x^2 + 32.3217x \]

For a given constant ZDR, the value of Z will scale with NW so T (in dB) is related to NW (in mm⁻¹ m³⁻¹) by the following formula (still assuming μ=5):

\[ NW = 8000 \cdot 10^{(T-T_0)/10} \]

With \(T_0 = 42.34\) at C-band for \(\mu=5\). If another value of \(\mu\) is assumed (\(\mu=0\) for instance), then the coefficients of P and the value of \(T_0\) change.

The optimal T (T_OPT), or equivalently the optimal NW (NW_OPT), and its error, are retrieved by minimizing the following cost function over a running sub-domain of the radar PPI (a, say, 5x5 km² Cartesian neighbourhood):

\[ \text{RMS}^2 = \frac{1}{N} \sum_{i=1,N} (Z_{\text{DR,OPT}}(i) - Z_{\text{DR}}(i))^2 \]

where ZDR OPT(i) are the observed values of ZDR in the 5x5 km² neighbourhood of the considered pixel and ZDR(i) are the theoretical ZDR values obtained via Eq. 4 for a given T and the observed ZH(i). T varies between 22 dBZ and 62 dBZ, which corresponds to an NW varying between 80 and 800,000 mm⁻¹ m³⁻¹ or, equivalently, log₁₀(NW) varying between 4.9 and 8.9 log₁₀(m⁻³). Because the neighbourhood is Cartesian, it is computationally extremely advantageous to start by projecting the polar grids of ZH and ZDR on 1km² Cartesian grids. This is done by reconstructing ZV (ZV = ZH – ZDR), expressing ZH and (reconstructed) ZV in linear units (mm⁻¹ m³⁻¹), averaging them on 1km² Cartesian grids and finally re-computing ZH and ZDR in dBZ and dB. A simple arithmetic average is used here, differences with more elaborate schemes (e.g. Cressman) were considered to be negligible. Beside practical considerations, the prior Cartesian projection contributes to reducing the noise as many 240mmx0.5° polar pixels fall inside 1km² Cartesian pixels up to long ranges. The minimization is started if at least 5 valid pixels (among a maximum of 25) are available in the neighbourhood. By valid, we mean in rain, non-attenuated (ϕDP < 15°) and with Z İ larger than 20 dBZ. The ϕDP threshold stems from the fact that ZZDR is extremely sensitive to ZDR biases and that differential attenuation correction procedures do not always yield precisions better than 0.2 dB.

Once the optimal T (T_OPT) and its error have been found, then the rainfall rate, and its error, of the central Cartesian pixel are simply obtained by converting the Cartesian reflectivity (ZH) with the following relationship:

\[ Z_H = \alpha R^{1.5} \]

The 1.5 exponent arises from the assumption of a normalized gamma DSD and the α coefficient is equal to 138\[(8000 / NW_{\text{OPT}})\] corresponding to an assumed value of 5 for \(\mu\).

3. Dataset, domain and comparison methodology

The two algorithms have been implemented on the French C-band polarimetric Trappes radar. The quality of the radar has been thoroughly assessed by Gourley et al. (2006). The polarimetric data (ZH, ZDR, ρHV and ϕDP) are available on polar PPIs having a range and azimuth resolution of 240 m and 0.5°, respectively. As mentioned before, the two algorithms require, as a first step, identification and rejection of
non-rain echoes such as ground-clutter, clear-air, bright band, snow, hail, ... Then, the two algorithms are applied on the remaining pixels. Finally all outputs of both algorithms were interpolated into a 1km² Cartesian grid.

The evaluation of the two algorithms is carried out for each hourly time step. The region around the Trappes radar is densely equipped with several rain gauge networks managed by several authorities. This validation study is based on the networks operated by Météo France, CEMAGREF and water sewage agencies. Overall, there are about one hundred rain gauges recording hourly rainfall accumulation within a distance of 100 km from the radar site. 12 episodes of the year 2005 have been selected. They represent the most intense events of the year 2005. The most spectacular event of deep convection happened on the 23 June 2005 and generated a maximum hourly rainfall accumulation of 51 mm in one hour.

4. Discussion on the calibration of the polarimetric variables

Atlas 2002: « After 56 years of research in radar meteorology, we have still failed to find a reliable and universally applicable method of radar calibration. »

Polarimetry offers new perspectives to calibrate the horizontal reflectivity of weather radars. The technique, referred to as the “consistency relationship” (Gorgucci et al. 1992; Goddard et al. 1994), relies in the redundancy between $Z_H$, $Z_{DR}$ and $K_{DP}$ in rain. If $Z_{DR}$ is well calibrated and $K_{DP}$ well estimated and unbiased, then the value of $Z_H$ can be predicted. If the predicted value of $Z_H$ differs from the observed one, then the difference is attributed to a radar miscalibration. In practice, an integrated form of the consistency relationship is used in which $\Phi_{DP}$ and not $K_{DP}$ is used which avoids all the difficulties (noise and bias) inherent in the $K_{DP}$ estimation. A thorough description of the operational implementation of the technique is given in Gourley et al. (2009). The calibration of horizontal reflectivity through the application of the consistency relationship requires that $Z_{DR}$ is well calibrated. The classical procedure to calibrate $Z_{DR}$ consists in collecting data at vertical incidence, at 90° elevation angle, while keeping the antenna rotating in azimuth. This way, even in the presence of canting of the drops or wobbling of the antenna, the expected mean $Z_{DR}$ is zero. Any departure from zero is considered as a system bias and is subsequently corrected for. Recent work with operational radars (Sugier and Tabary 2006), however, have clearly demonstrated the impact of the radome peel joints on the $Z_{DR}$ measurements. These azimuth- and elevation-dependent disturbances have a typical magnitude of up to ±0.3 dB. The repeatability of the patterns (Gourley et al. 2006) suggests an empirical correction method. In that context, a new $Z_{DR}$ calibration procedure has been proposed (Segond et al. 2007) where the intrinsic $Z_{DR}$ of high-SNR, close-range and rainy pixels having a reflectivity between 20 and 22 dBZ is assumed to have a mean value of 0.2dB. This assumption is supported by long time series of disdrometer data in France and in the UK.

Figure 1 shows the azimuth-dependent bias on $Z_{DR}$ obtained for the year 2005 at 1.5° elevation angle. Segond et al. (2007) have shown that this curve was fairly stable all over the year 2005.

![Figure 1: azimuth-dependent bias on Z_{DR}](image1)

Each line corresponds to one estimation of the reflectivity bias at a given instant (corresponding to an average over one PPI). All lines are comprised between −0.5 and −1.5 dB, meaning that the radar was too hot. The limited number of available estimations is due to the stringent criteria imposed to select the data. Gourley et al. (2009) did not attempt to stratify their results with azimuth. Yet, considering the azimuth-dependent biases on $Z_{DR}$, the bias on $Z_H$ is also expected to be azimuth-dependent. Indeed, why would only $Z_H$ be affected by azimuth-dependent biases? This analysis leads to the second approach to radar reflectivity calibration (Testud, personal communication). The distributions of the $N_e$ values inferred in stratiform regions by the ZPHI algorithm.
have been computed for each azimuth on the same day as before (4th of July) and compared to a representative, disdrometer-retrieved N₀. The differences between the radar- and the disdrometer-retrieved N₀ are attributed to miscalibration of the horizontal reflectivity. The results are overlaid on Fig. 2. The agreement with the first approach is excellent. All estimations obtained with the first approach lie within the range of the azimuth-dependent biases retrieved with the second approach. In their paper, Gourley et al. (2009) show that the Z₁₀ calibration bias is fairly constant during all events of 2005. Therefore, all Z₁₀ values used in the present study have been corrected according to the wavy curve of Fig. 2.

5. Results

Figure 3 shows the synthesis of the hourly results over all 12 episodes: 6 QPE candidates are presented:
- The conventional Z=282R^{1.66} estimator (top left);
- The conventional (Z=282R^{1.56}) estimator with real-time hourly rain gauge adjustment (bottom left).
- The adjustment factor for the hour h is computed based on past (from h-16 to h-1) ratios between radar and gauge accumulations. “More recent” hours receive more weight in the estimation than “older” hours.
- ZZDR with no attenuation correction (middle column, top);
- ZZDR with attenuation correction (middle column, bottom);
- ZPHI® with attenuation correction only and the climatological Z=282R^{1.56} relationship (top right);
- ZPHI® with attenuation correction and N₀* adjustment (bottom right).

The x-axis corresponds to the hourly rain gauge accumulations and the y-axis to the hourly radar estimations. The horizontal and vertical scales are logarithmic. Both the Normalized Bias (NB) and the correlation coefficient (corr) are given on each graph. We recall that:

\[ NB = \frac{R}{G} - 1 = \frac{1}{N} \sum_{j=1}^{N} \frac{R_j}{G_j} - 1 \]

\[ corr = \frac{\sum_{j=1}^{N} (G_j - \bar{G})(R_j - \bar{R})}{\sqrt{\sum_{j=1}^{N} (G_j - \bar{G})^2 \sum_{j=1}^{N} (R_j - \bar{R})^2}} \]

where (Gᵢ, Rᵢ) are the various radar and rain gauge couples. N is given on each graph (N points). A positive NB reveals an overestimation by the radar and a negative NB an underestimation. NB and corr are given for all hourly rain rates and also for rain gauge rates above 1 mm h⁻¹. The form of each point (cross or square) reveals the mean hourly attenuation (estimated by ZPHI). A square (resp. cross) corresponds to a mean hourly attenuation larger (resp. smaller) than 1.5 dB. The color on ZZDR graphs gives the relative error on the estimation (as explained in previous sections). Black (resp. red) means low (resp. high) estimation uncertainty. The color on ZPHI graphs represent the percentage of triggering of the ZPHI® algorithm within the hour. The ideal situation is 100% (red), where the algorithm was triggered at all 5’ time steps within the hour.

The most striking and, as developed below, still unexplained feature is the systematic underestimation of the conventional estimator. The NB is about –40%. It is only partially reduced with the real-time hourly gauge adjustment (-20%). This may be due to the fact that the operational adjustment procedure relies only on past hours and does not consider the current hour. In contrast, all 4 polarimetric algorithms show no bias. The comparison of the conventional estimator (NB = -40%) with ZPHI® with attenuation correction only (NB = 0) should lead to the conclusion that the –40% bias of the conventional estimator is essentially due to (non corrected) rain-induced attenuation.

On the other hand, the comparison of the conventional estimator (NB=-40%) with ZZDR without attenuation correction leads to the conclusion that the –40% bias of the conventional estimator is due to (non adjusted) ZR relationship.

Further investigations are currently underway to arrive at a global consistent picture.

Overall, the scores obtained with ZPHI® and ZZDR are comparable. The correlation coefficient varies between 0.79 and 0.88 and the NB is in the range ±10%. There is a clear benefit in including the N₀ adjustment in ZPHI® and in including the attenuation correction in ZZDR. Even though no specific scores were computed for the most intense rain rates, its qualitative evidence from Fig. 3, that ZPHI® is the algorithm that performs the best, which is no surprise given the way it is designed. On the other hand, the analysis of individual events shows that ZZDR gets better scores than ZPHI® for events with low-to-moderate rain rates.

6. Conclusions and outlook

In conclusion, the integrated ZPHI® and ZZDR techniques appear as very promising techniques to deal with the noise inherent with the polarimetric measurements. It should be kept in mind that both algorithms are only valid in rain (and not in the bright band, snow, hail, ...). The quality of the rainfall estimation is shown to be critically dependent upon the calibration of Z₁₀ (ZPHI® and ZZDR) and Z₁₀ (ZZDR only). The calibration biases, which are shown to be azimuth-dependent due to the radome structure, have to be monitored operationally and corrected for. If calibration issues are properly addressed, then both algorithms are good operational candidates for rain
rate estimation with a C-band polarimetric radar. With the C-band Trappes radar, we have shown that ZPHI® improves the rainfall estimation for rain rates larger than 3 – 4 mm h⁻¹ (at C-band), which can be considered as moderate to heavy rain rates for northern France. That rain rate threshold for ZPHI® (linked to the required φDP phase rotation) is expected to be higher (resp. lower) at S-band (resp. X-band). ZZDR is the best candidate for low-to-moderate rain rates (up to 3 – 4 mm h⁻¹). The only limiting factor for the application of ZZDR to higher rain rates is the rain-induced attenuation on ZDR (and ZH but to a lesser extent) and the uncertainties inherent to attenuation correction procedures. If the remaining error on the attenuation-corrected ZDR can be reduced to less than 0.2 dB, then ZZDR should perform as good as ZPHI®. In the current state-of-the-art of both algorithms, it appears that the ideal algorithm would probably be a combination of both.

In the future, we plan on continuing the evaluation of ZPHI® and ZZDR on more radars and more cases. The Hogan (2007) algorithm will also be included in the evaluation. The idea is to design a robust, “all rain rates” algorithm for operational rain rate estimation at C and S band.

Appendix : Operational monitoring of dual-polarization variables at Météo France

Given, the extremely high sensitivity of dual-polarization algorithms to biases on ZDR, φDP, ρHV and, to a lesser extent ZH, the operational introduction of dual-polarization prompted the definition and production of monitoring indicators on a daily basis. The idea was to detect as early as possible a failure in the radar system (rotary joint failure, wave guide losses, TR tube failure, …) that would cause problems on subsequent products. Several examples of such chains of consequences can be drawn from the last 5 years of dual-polarization operations at Météo France. The monitoring indicators that were designed and coded are the following (many of them are described in Gourley et al. (2006)) :

- **Mean ZDR at 90°**: the 90° tilt is revisited every 15 minutes on all 10 French polarimetric radars. The intrinsic value of ZDR at 90° is expected 0 dB in precipitation, so that any non-zero value is attributed to miscalibration of the radar system. The mean daily value as well as the total number of points are computed and stored. Any significant departure (± 0.5 dB) from the last available bias estimation is detected and the maintenance team is alerted. The operational use of all dual-polarization variables (ZDR, ρHV and φDP) is inhibited until the problem has been understood.

- **Mean ZDR for ZH between 20 and 22 dBZ in close-range, high-SNR, rain gates.** The mean expected value is 0.2 dB so that any departure from that value is considered to be a system miscalibration. The mean ZDR value is this time computed both as a function of azimuth and elevation. Gourley et al. (2006) have shown indeed that the radome may have an influence of the ZDR biases (typically ± 0.3 dB). In addition to the mean calibration bias curves, which are needed for correction purposes and, again, functions of azimuth and elevation, a single mean value is computed, for alerting the maintenance team, should a sudden and significant change be detected (± 0.5 dB).

- **ZDR in sun spikes on sunrise and sunset.** Holleman et al. (2009) have demonstrated the potential of that approach to calibrate the (differential) reception chain of polarimetric systems. The advantage over the previous approaches is that it provides information no matter what the weather situation is (rainy vs. not rainy). Holleman et al. (2009) typically had 10 to 20 hits per day for the French Trappes radar, which performs about 15 different rounds at different elevation angles every 15 minutes.

- **φDP offsets.** The φDP offset is computed from the first available precipitation gates along the ray. The φDP offset is stratified as a function of azimuth and elevation. A mean single value is computed and alerts are triggered if a sudden and significant variation with respect to the previous estimation is detected. As for the other parameters, an anomaly that is detected leads to the deactivation of dual-polarization exploitation.

- **Upper 80% quantile of all ρHV values in close-range, high-SNR pixels in rain.** A 0.99 value is expected in that case. The reason for taking the upper 80% quantile of the qualifying pixels is the very asymmetrical distribution of ρHV, which makes a few percent of outliers have a devastating influence on the simple mean and even median averages. Any significant drop of the mean ρHV in rain (below 0.95) is considered as a failure.

- **Mean ZDR at lowest elevation at several close ranges (0 – 3 km, 3 – 6 km, 6 – 9 km).** At such ranges at the lowest elevation angle, all gates are very likely to be contaminated by ground clutter. The intrinsic value of ZDR in ground clutter was empirically found to be close to zero dB (± 3 dB). This monitoring indicator was developed to detect a TR tube failure on one of the two channels, that would cause ZDR to reach unrealistically high or low values in close-ranges.

- **Noise at horizontal and vertical polarizations.**
Figure 3: Overall hourly radar–rain gauge comparison results for all 12 events of 2005. See the text for more information on the colors and scales.

References


