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 ϕ_{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 (ρ_{HV}, no units) and the differential phase (Φ_{DP}, expressed in degrees). ρ_{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 (Bringi and Chandrasekar 2001), Z_{DR} is a good estimate of the mean drop diameter. Φ_{DP}, the phase difference between the H and the V wave (Φ_H-Φ_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.

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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 ϕ_{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 ($Z=282R^{1.66}$) 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_0^*-normalized relationships between Z_H (intrinsic horizontal reflectivity in mm^6 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}) :

$A_H = a(T). N_0^{*(1-b(T))}.K_{DP}^{b(T)}$

$K_{DP} = c(T). N_0^{*(1-d(T))}.Z_H^{d(T)}$

$R = e(T). N_0^{*(1-f(T))}.Z_H^{f(T)}$

where a, b, c, d, e and f are known functions of temperature only, and N_0^* (or N_w) is the normalised drop concentration..

The ZPHI algorithm, because it relies on integrated forms of the equations above mitigates the unavoidable noise on the polarimetric variables (especially K_{DP}). The required assumptions, however, are that N_0^* remains constant over a certain segment [r_0; r_1] and the differential phase shift over the [r_0; r_1] segment exceeds significantly the typical noise on ϕ_{DP} measurements, so that a minimum of $\Delta\phi_{DP}$ = 6 degrees phase shift is required for the algorithm to be triggered. Even though any estimated N_0^* value can, to a certain extent, be extrapolated in range and / or azimuth, the constraint on the required minimum $\Delta\phi_{DP}$ 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 N_0^* 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 Z_H and ϕ_{DP} and not Z_{DR}, 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 N_0^* 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 $\log_{10}(N_0^*)$ of 6.3 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 Z_H and Z_{DR} :

$$Z_H(dBZ) = P(\log_{10}(Z_{DR}(dB))) + T$$

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

$$P(x) = -3.1317x^3 + 6.4566x^2 + 32.3217x$$

For a given constant Z_{DR} , the value of Z will scale with N_W so T (in dB) is related to N_W (in $mm^{-1}\ m^{-3}$) by the following formula (still assuming μ=5) :

$$N_W = 8000 * 10^{((T-T_0)/10)}$$

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

The optimal T (T_{OPT}), or equivalently the optimal N_W (N_W^{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) :

$$RMS^2 = (1/N)*\Sigma_{i=1...N} (Z_{DR}^{OBS}(i) - Z_{DR}^{T}(i))^2$$

where $Z_{DR}^{OBS}(i)$ are the observed values of Z_{DR} in the 5x5 km² neighbourhood of the considered pixel and $Z_{DR}^{T}(i)$ are the theoretical Z_{DR} values obtained via Eq. 4 for a given T and the observed $Z_H(i)$. T varies between 22 dBZ and 62 dBZ, which corresponds to an N_W varying between 80 and 800,000 $mm^{-1}\ m^{-3}$ or, equivalently, $\log_{10}(N_W)$ varying between 4.9 and 8.9 $\log_{10}(m^{-4})$). Because the neighbourhood is Cartesian, it is computationally extremely advantageous to start by projecting the polar grids of Z_H and Z_{DR} on 1km² Cartesian grids. This is done by reconstructing Z_V ($Z_V = Z_H - Z_{DR}$), expressing Z_H and (reconstructed) Z_V in linear units ($mm^6\ m^{-3}$), averaging them on 1km² Cartesian grids and finally re-computing Z_H and Z_{DR} 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 240mx0.5° 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 (ϕ_{DP} < 15°) and with Z_H larger than 20 dBZ. The ϕ_{DP} threshold stems from the fact that ZZDR is extremely sensitive to Z_{DR} 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 (Z_H) with the following relationship :

$$Z_H = a\ R^{1.5}$$

The 1.5 exponent arises from the assumption of a normalized gamma DSD and the a coefficient is equal to $138\sqrt{[(8000 / N_W^{OPT})]}$ corresponding to an assumed value of 5 for μ.

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 (Z_H, Z_{DR}, ρ_{HV} and ϕ_{DP}) 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 raingauge 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 rain 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 Φ_{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 th e 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.

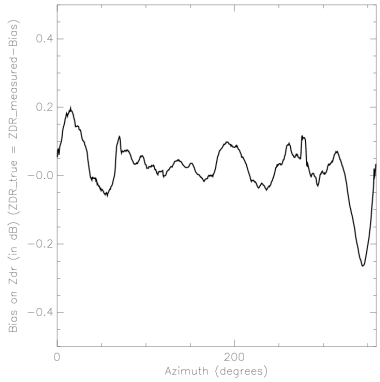

Figure 1 : azimuth-dependent bias on Z_{DR}.

All measured Z_{DR} used in the present study have been corrected with that empirical curve. The calibration of the horizontal reflectivity (Z_H) has been performed with two independent methods. Gourley et al. (2008), on the one hand, have applied the consistency relationship to all events of the year 2005 collected by the Trappes radar at 1.5° elevation. Z_{DR} data were first corrected according to Fig. 1.

Figure 2 shows their estimates for the 4th of July (straight horizontal lines).

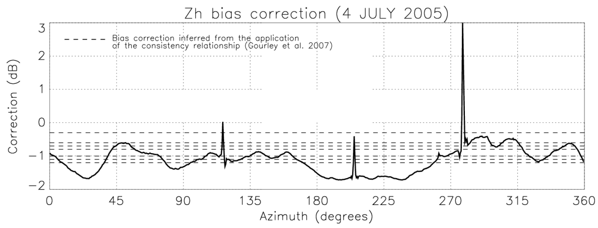

Figure 2 : azimuth-dependent bias on Z_H.

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_V 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_0^* 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 N_0^*. The differences between the radar- and the disdrometer-retrieved N_0^* 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 Z_H calibration bias is fairly constant during all events of 2005. Therefore, all Z_H 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 ($Z=282R^{1.66}$) 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 $Z=282R^{1.66}$ 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 :

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

$$corr = \frac{\sum_{j=1}^{N}(G_j - \overline{G})(R_j - \overline{R})}{\sqrt{\sum_{j=1}^{N}(G_j - \overline{G})^2}\sqrt{\sum_{j=1}^{N}(R_j - \overline{R})^2}},$$

where (G_j, R_j) 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, it is qualitatively evident 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 betters 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 Z_H (ZPHI® and ZZDR) and Z_{DR} (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 ϕ_{DP} 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 Z_{DR} (and Z_H but to a lesser extent) and the uncertainties inherent to attenuation correction procedures. If the remaining error on the attenuation-corrected Z_{DR} 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 aim 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 Z_{DR}, ϕ_{DP}, ρ_{HV} and, to a lesser extent Z_H, 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 Z_{DR} at 90°** : the 90° tilt is revisited every 15 minutes on all 10 French polarimetric radars. The intrinsic value of Z_{DR} 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 (Z_{DR}, ρHV and ϕ_{DP}) is inhibited until the problem has been understood.
- **Mean Z_{DR} for Z_H 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 mis-calibration. The mean Z_{DR} 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 Z_{DR} 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).
- **Z_{DR} 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.
- **ϕ_{DP} offsets**. The ϕ_{DP} offset is computed from the first available precipitation gates along the ray. The ϕ_{DP} 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 ρ_{HV} 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 ρ_{HV}, 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 ρ_{HV} in rain (below 0.95) is considered as a failure.
- **Mean Z_{DR} 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 Z_{DR} 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 Z_{DR} to reach irrealistically high or low values in close-ranges.
- **Noise at horizontal and vertical polarizations.**

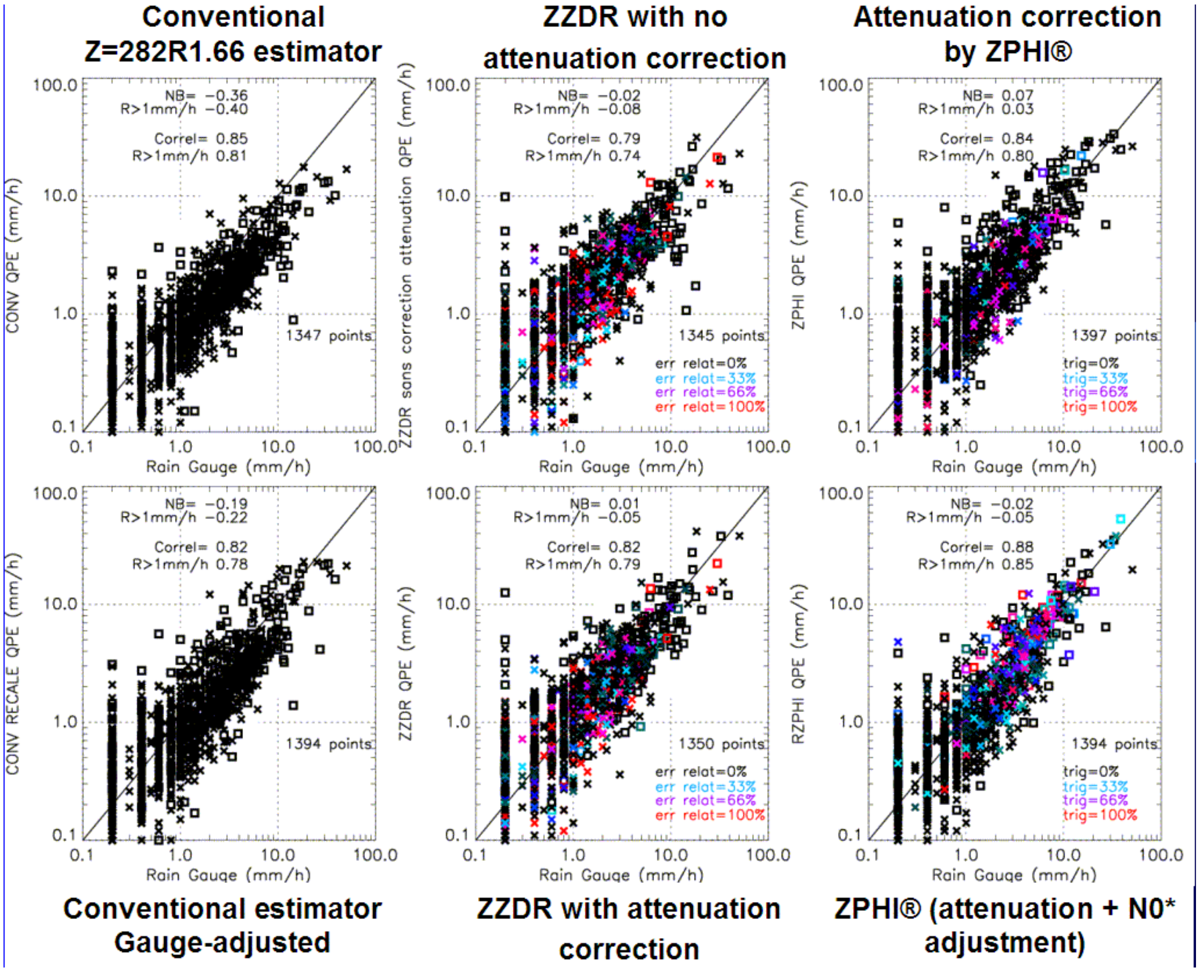

Figure 3 : Overall hourly radar – rain gauge comparison results for all 12 event of 2005. See the text for more information on the colors and scales.

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