P6R.12 CONDITIONAL EVALUATION OF CONVENTIONAL VS. POLARIMETRIC QPE at C-band

Wiwiana Szalinska[1,2)], Pierre Tabary[2)], and Hervé Andrieu[3)]

[1)] Cemagref, UR Hydrosystèmes et bioprocédés, Antony Cedex, France
[2)] Meteo-France, DSO, Centre de Meteorologie Radar, Trappes, France
[2)] Laboratoire Central des Ponts et Chaussées, Division Eau et Environnement, Bouguenais, France

1. INTRODUCTION

Measurement of rainfall with conventional radars is subject to numerous sources of errors. Significant progress has been made during recent decades to cope with these error sources: partial beam blockage, VPR influence, anomalous propagation, attenuation, etc. The physics of the conventional radar measurement is well established, allowing the design of radar simulators (Caumont et al., 2005). Despite the progress, some measurement difficulties have not yet been solved. The drop size distribution (DSD) is subject to variations and the attenuation correction algorithms (for C and X band radars) are subject to instabilities which prevent their operational application. Dual-polarization which has been a very active research field during the last twenty years overcome these problems and may improve the accuracy of rainfall measurement (Bringi and Chandrasekar, 2001).

Different approaches have been proposed to benefit from polarimetric parameters for rain rate estimation. A frequent approach extends the conventional R(Z) relationship by expressing rainfall rate R as a function of polarimetric radar parameters. Three types of relationships have been proposed: $R(Z,Z_{DR})$, $R(K_{DP},Z_{DR})$ and $R(K_{DP})$ (Ryzhkov et al., 2003). Validation studies show that polarimetric relationships result in an improvement of rainfall measurement in comparison with R(Z) relationships (to include two references). These findings have been confirmed by the JPOLE experiment (Ryzhkov et al., 2003) who compared various polarimetric relationships based on a large data set measured by the S-Band radar in Oklahoma. This data set is mostly composed of convective rain events but also includes stratiform situations. The authors conclude that most of the polarimetric algorithms perform better than conventional R(Z) at distance less than 125 km and that the best results are obtained with a $R(Z,K_{DP},Z_{DR})$ algorithm. The improvement was shown to be significant for stratiform rain events. Alternative approaches have been proposed. Brandes et al. (2003) base their rainfall estimation scheme on DSD retrieval. Testud et al. (2000) have developed the algorithm ZPHI which uses polarimetric data to reduce the uncertainty of the classical R(Z) estimate and to correct radar data for attenuation which is of particular importance for C and X band radar. ZPHI has been successfully tested and compared to a conventional $R(K_{DP})$ approach (Le Bouar et al., 2001).

In order to objectively assess the benefits of dual-polarization at C-band in an operational context, a one-year experiment has been set up 30 km South West from Paris starting January 2005. Specification of the radar and scanning strategy of Trappes radar are summarized in the Table 1.

Table 1 Trappes C-band GEMATRONIK radar specification and scanning strategy

RADAR SPECIFICATION				
Antenna diameter	3.7 m			
Beam width (3dB) H and V	< 1.1°			
Pulse width	2 microseconds			
Frequency	5.640 GHz			
Wavelength	5.31 cm			
PRF	Staggered-PRT : 379, 321 and 305 Hz			
Range resolution	240 m			
Scanning strategy				
H → H+5	H+5→ H+10	H+10→H+15	H+15→H+20	…
2.5, 6.5,0.8 1.5, 90., 0.4	2.5, 4.5, 0.8, 1.5, 9.0, 0.4	2.5, 3.6, 0.8, 1.5, 7.5, 0.4	2.5, 6.5, 0.8, 1.5, 90., 0.4	…

Three different Quantitative Precipitation Estimations (QPE) are produced in real-time on a 5-minute basis: the first one, referred to as CONV, is an estimation that is based entirely on horizontal reflectivity. It serves as the benchmark to beat in the conditional evaluation. The two other estimations, referred to as POL1 and POL2, are obtained with ZPHI algorithm (Testud et al., 2000) that is implemented on the real time data stream.

The three radar QPEs are compared on an hourly basis with a dense Meteo France raingauge network of about 100 raingauges within a distance of 100 km from the radar (Fig. 1). All the recorded rainfall episodes are included in the comparison. The basic idea of the validation procedure is to perform a conditional evaluation that is designed to isolate and quantify the following error sources: ground clutter, attenuation, DSD variation, bright band contamination and partial beam blocking. From isolated comparison points concerned with each type of error or free of any error, the capability of polarimetric data for each condition is evaluated.

Corresponding author: Wiwiana Szalinska,
Address: Centre de Meteorologie Radar, DSO, Meteo France, 7 rue Teisserenc-de-Bort 78195, Trappes, France;
email: wiwiana.szalinska@meteo.fr

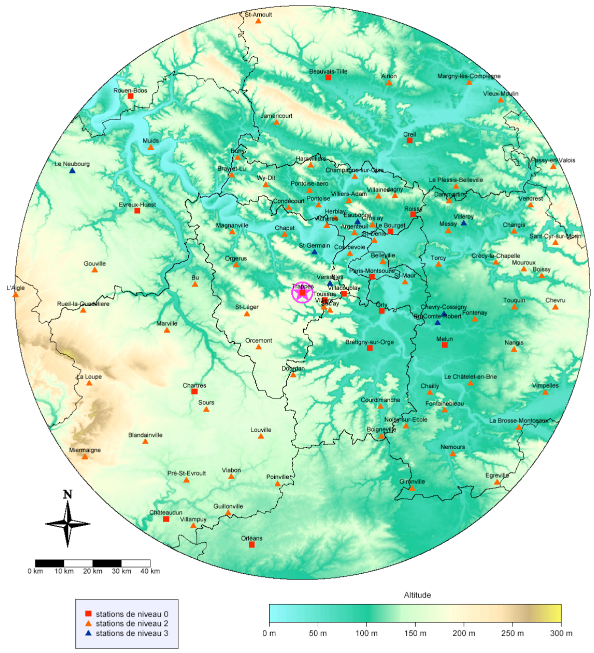

Fig 1 Meteo France raingauge network within the distance of 100 km

2. RADAR QPE ALGORITHMS

2.1 Conventional rainfall estimate

The new operational radar QPE algorithm developed by Meteo France (Tabary et al. 2005) currently corrects for ground-clutter, orogenic partial beam blocking, advection and VPR effect. Each pixel of each PPI is corrected for the various identified error source and the final surface rainfall estimation is obtained through a weighted linear combination of all available measurements. In conventional estimate (CONV) the rainfall rate is recalculated from the horizontal reflectivity using the relation $R=3.34*10^{-2}Z^{0.6}$. The coefficient in the Z-R relation (a=282, b=1.66) were chosen by analyzing disdrometer measurements of convective and stratiform rainfall during three weeks in 1999 (Testud, personal communication).

2.2 Polarimetric rainfall estimate

Before entering the QPE algorithm chain polarimetric radar measurements are processed by ZPHI algorithm (Testud, 2000, Le Bouar et al. 2001). 'ZPHI' is a rain profiling algorithm that retrieves profiles of the rainfall rates. The base of ZPHI algorithm is an inverse model of three empirical relationships between the integrated parameters of DSD - rainfall rate R (mm h^{-1}), equivalent reflectivity Z_e (mm^6 m^{-3}), specific attenuation A (dB km^{-1}) and specific differential phase shift K_{dp} (deg km^{-1}). The primary products of ZPHI algorithm are the profile along the beam of specific attenuation and the intercept parameter (N_0*) of the normalised gamma form of DSD. The rainfall rate is estimated through the rainfall to attenuation relationship adjusted for the value of N_0*.

POL2 is the polarimetric estimation of the surface rainfall accumulation that takes full advantage of ZPHI algorithm including correction for attenuation and adjustment of the N_0* parameter. The rainfall rate is estimated through an R-A relation $R = c[N_0^*]^{1-d} A_h^{\,d}$ where *c* and *d* coefficients depend on temperature (Testud et al*.* 2000, Le Bouar et al*.* 2001).

POL1 only includes the correction for attenuation estimated by ZPHI and rainfall is calculated through Z-R relation.

2.3 Comments

It is important to notice that all pixels of the three QPEs come from the same tilt, which ensures that they have the same properties in terms of ground clutter, attenuation, height, degree of blocking, DSD variation, and VPR effect. Differences are attributed to the rainfall estimation and applied corrections schemes.

The coefficients of Z-R relation used to estimate rainfall in CONV and POL1 correspond to the logarithm value of the 'normalized' intercept parameter of gamma distribution of 6.3 m^{-4}. This value is also taken as a fixed value for N_0^* to run ZPHI when differential phase shift (Δ_{DP}) is smaller than 6º. In such cases N_0* can not be derived with sufficient accuracy due to the direct relation between error in N_0* and uncertainty in estimated Δ_{DP} (see Le Bouar et al., 2001)

3. VALIDATION PROCEDURE

The conditional evaluation consists of grouping radar measurements that have the same characteristics. Criteria required to divide the data set into subsets are either generated by the radar QPE procedure or by the ZPHI algorithm.

In this paper conditioning was aimed at investigating the improvement of polarimetry for correcting for attenuation and DSD variability while reducing the other source of errors.

As the validation concerns hourly accumulation, a vital stage of conditioning is temporal integration of error characteristics. While it is not an issue for fixed and permanent errors like ground clutters or shielding, it plays a major role for meteorological and rainfall dependent source of errors like attenuation or DSD. This is done differently for each of the error source.

The criteria to survey the variation in DSD were values of the 'normalized' intercept parameter N_0^* retrieved in ZPHI algorithm. The discriminator for N_0^* parameter over an hour is computed as mean of twelve N_0^* values weighted by the rainfall rate. This formulation aims to characterize the hourly rainfall accumulation with the value of N_0* retrieved for the most intensive among twelve estimated rainfall rates.

To discriminate and stratify the severity of attenuation affecting radar measurements over an hour, a special function was applied to weight mean attenuation by the rainfall intensity. The form of the weighting function was deduced by assuming that Z-R relationship provides a good estimate of raingauge measurement so that radar rainfall estimate (C_R) differs from raingauge (C_G) only by loss in reflectivity caused by attenuation

$$C_R = R(Z^{TRUE} - ATT_{dB}) = \left(\frac{Z^{TRUE}\cdot 10^{\frac{-ATT_{dB}}{10}}}{282}\right)^{\frac{1}{1.66}} = C_G \cdot 10^{\frac{-ATT_{dB}}{16.6}}$$

Mean attenuation over an hour would be though a logarithm of hourly radar estimates to hourly raingauge estimate obtained by cumulating 5-min estimates. Each of the 5-min radar estimates could be expressed as a function of 5-min raingauge rainfall accumulation and 5-min path integrated attenuation.
To evaluate severity of attenuation in reference to rainfall intensity, 5-min raingauge rainfall measurements were expressed by 5-min POL2 rainfall estimates that believed to be the best surface rainfall estimates. Hourly mean value of attenuation was though calculated as:

$$\overline{ATT_{dB}} = -16.6\cdot\log_{10}\left[\frac{\sum_{i=1}^{12} POL_2(i)\cdot 10^{\frac{-ATT(i)}{16.6}}}{\sum_{i=1}^{12} POL_2(i)}\right]$$

where *i* is the number of radar to raingauge observations, POL2(i) and ATT(i) are 5-minutes second polarimetric estimate and path integrated attenuation respectively given by ZPHI algorithm.

4. RESULTS

The multi-event data set consists of 22 rainfall events recorded from December 2004 up to August 2005 comprising a wide spectrum of rainfall from light stratiform to heavy convection as illustrated by a case on 28 July, when raingauges recorded 18 mm of rainfall during 6 minutes. The data set contained 4137 couples of hourly raingauges and radar accumulations where all three radar estimates were available (CONV, POL1 and POL2) and 8082 couples where only CONV and POL1 could be compared (POL2 was not available due to different then rain precipitation type and by this inadequateness of the inverse model employed in ZPHI). Errors that may arise due to the scaling of radar-based estimates down to the raingauges were neglected. Comparisons between raingauges data and radar QPEs were performed for selected subsets having common characteristics. The examined criteria to measure the quality of different rainfall estimators were normalized bias *NB* and Nash criterion *N* (Nash et al. 1970)

$$NB = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(R_r^{\,i} - R_g^{\,i}\right)}{\frac{1}{N}\sum_{i=1}^{N} R_g^{\,i}} \qquad N = 1 - \frac{\sum_{i=1}^{N}(R_r^{\,i} - R_g^{\,i})^2}{\sum_{i=1}^{N}(R_g^{\,i} - \overline{R}_g)^2}$$

where R_r – rainfall estimated by radar and R_g – rainfall measured by raingauges. The results are presented as radar to raingauge correlation plots with displayed values of sample size, correlation coefficient, RMSE and examined criteria. A scatter diagram of RMSE vs. correlation coefficient is also produced.

4.1. Attenuation conditioning

In the first conditioning analyzed data subset contained 39 comparison points affected by at least 3 dB of hourly mean attenuation. The comparison showed that significant improvement is obtained with polarimetric measurements (Fig. 2). Presence of attenuation mainly affects the normalized bias and this indicator was –0.43 for CONV, -0.03 for POL1 and 0.12 for POL2, meaning that the CONV estimate was underestimating raingauges by 43% on average. Also the other scores were better for polarimetric estimates, Nash coefficient in particular was 0.25 for CONV while 0.46 for both POL1 and POL2.

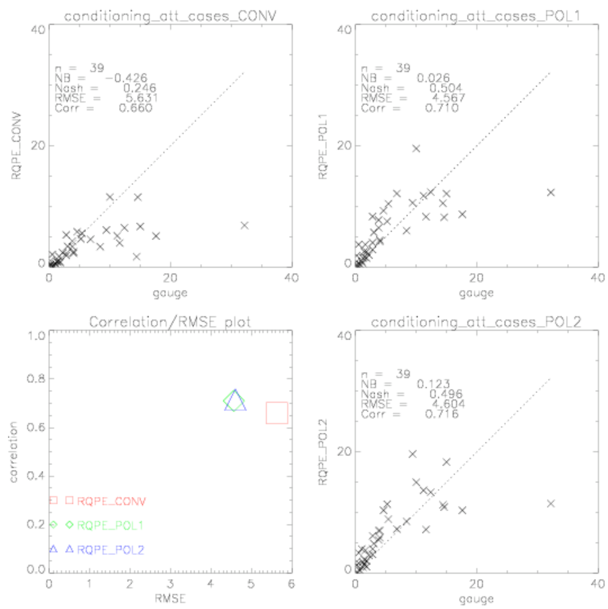

Fig. 2 Correlations plots and examined scores results for three radar estimates CONV, POL1 and POL2 versus raingauges measurements conditioned by value of attenuation (mean attenuation oven an hour ≥ 3dB).

4.2 DSD conditioning

Discriminating the dataset according to DSD variability was done using the weighted mean value of the N_0* parameter. The reference value for was log(N_0*)=6.3 m^{-4} which corresponds to the implicit value of the 'normalized' intercept parameter characterizing DSD in CONV and POL1. Once retrieved values of N0* were close to reference value, Z-R relationship was supposed to correspond well to the real rainfall characteristic. Values smaller then 6.2 meant more stratiform rainfall for which assumed Z-R relationship was likely to result in overestimation of rainfall rate. For values bigger then 6.4, typical for convective rainfalls, assumed Z-R might results in underestimation. This analysis were confirmed by conditional evaluation.

Selecting comparison pairs of mean attenuation less then 2 dB and mean value of N_0* parameter close to reference value, showed that in this 'ideal' conditions satisfied by 214 cases, all three estimates were of the same, good accuracy confirmed by the 0.5 of Nash criterion. No bias was observed for radar estimates, confirming adequateness of Z-R relationship (Fig. 3).

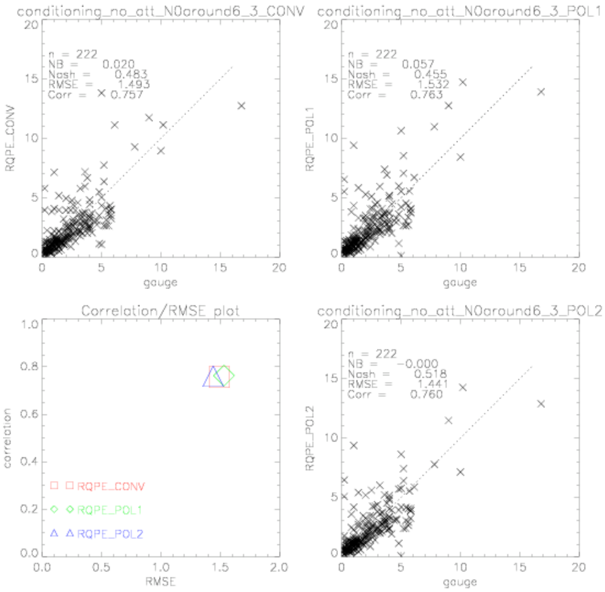

Fig. 3 Correlations plots and examined scores results for three radar estimates CONV, POL1 and POL2 versus raingauges measurements conditioned by absence of attenuation and mean value of log(N_0*) close to 6.3

Selecting comparison points of mean attenuation smaller then 2 dB and mean N_0* value smaller then 6.2 are presented on Fig. 4. They confirmed tendency to overestimate rainfall rate for CONV and POL1 (NB =0.32 for CONV and 0.47 for POL1). POL2 estimate, through tuning to retrieved N_0* value, showed little positive bias (0.12) but much satisfactory values of Nash coefficient +0.33 to be compared to the poor values obtained by CONV (0.08) and POL1 (–0.6).

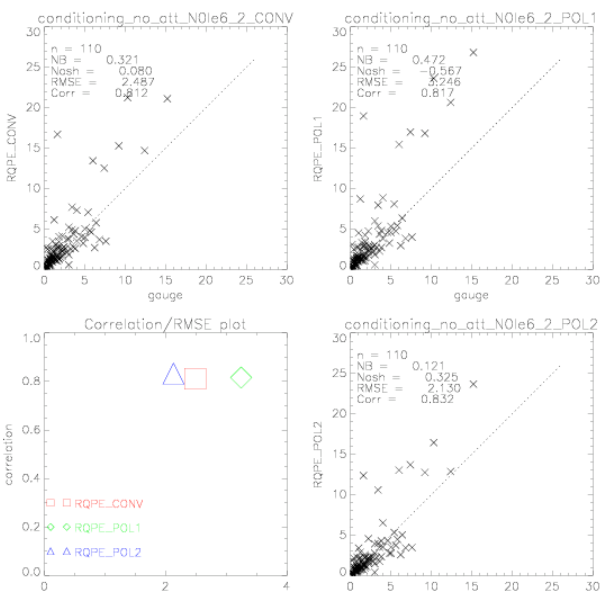

Fig. 4 Correlations plots and examined scores results for three radar estimates CONV, POL1 and POL2 versus raingauges measurements conditioned by absence of attenuation and of mean value log(N_0*) less then 6.2

Inversing condition on N_0* and selecting pairs characterized by bigger then 6.4 log(N_0*) values also confirmed expected underestimation generated by used Z-R relation (Fig. 5). It especially concerned the highest rainfall rates. Total underestimation was however not very significant (-0.13 for CONV) due to the fact that convective cells characterized by higher values of N_0* are usually related to stronger attenuation, so not many cases of intensive rainfall and small attenuation were observed. All three estimates were of good accuracy according to Nash criterion (around 0.5). The improvement introduced by N_0* adjustment mainly affecting correlation coefficient. Observed overestimation of POL2 estimates might be caused by the problems in retrieving the N_0* values in stratiform light rain caused by the increased of statistical error in Δ_{DP} estimation that is proportional to the N_0* retrieval error (Le Bouar et al., 2001)

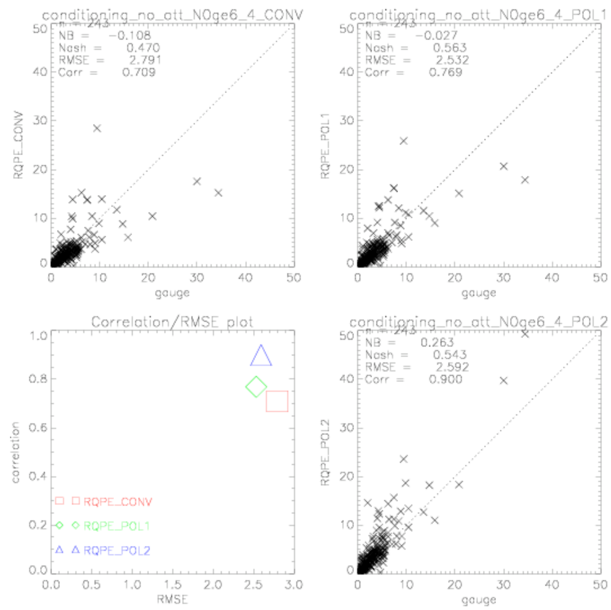

Fig. 5 Correlations plots and examined scores values for three radar estimates CONV, POL1 and POL2 versus raingauges measurements conditioned by absence of attenuation and mean value of log(N_0*) greater then 6.4

From subset of comparison points affected by mean attenuation bigger then 2 dB, three different N_0* characteristics were examined – values of log(N_0*) close to 6.3, smaller and bigger. Because attenuation is correlated with N_0*, the first two subsets were small and were evaluated together. The analysis confirmed expected performance. That is, for the cases of stratiform rain characterized by smaller values of N_0* but also affected by attenuation, two antagonistic processes can be observed. Not suitable Z-R relation causing overestimation and signal attenuation resulting in rainfall underestimation. Due to these effects, no bias and satisfactory value of Nash coefficient (0.36) were obtained for CONV in contrary to POL1 when effect of Z-R overestimation was enhanced by correcting reflectivity for attenuation (Fig. 6). Because of both attenuation correction and N_0* retrieval POL2 estimate reached very good accuracy of 0.7 Nash criterion value reducing overestimation caused by attenuation correction only .

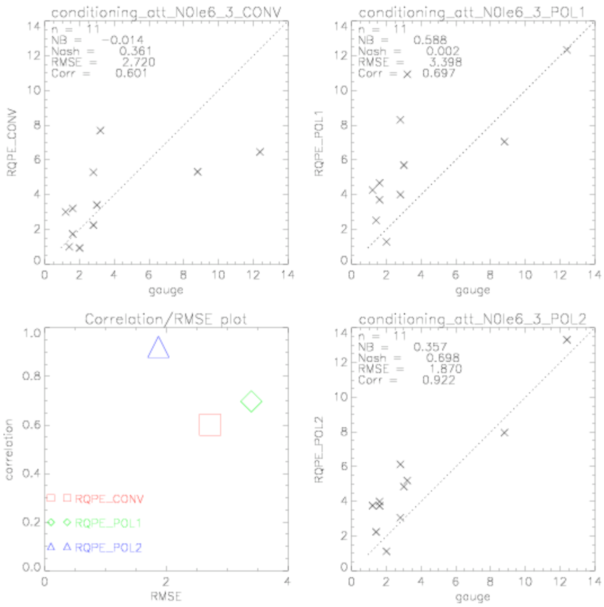

Fig. 6 Correlations plots and examined scores results for three radar estimates CONV, POL1 and POL2 versus raingauges measurements conditioned by presence of attenuation and mean value of log(N_0*) less then 6.3

Cases of big attenuation and big value of N_0* are the ones of the greatest concern as they are usually connected with strong convection and heavy rainfalls. They are also the most difficult to estimate. From multi-event data set, 20 comparison pairs were characterized by big attenuation of mean value bigger then 2 dB and by big values of 'normalized' intercept parameter N_0*. Results presented on Fig 7 confirmed the improvement introduced by polarimeric measurements for both correcting for attenuation in POL1 and correcting for attenuation and tuning N_0* in POL2. CONV estimate was severely underestimated by 46% on average because of attenuation and not suitable Z-R relation. Correcting for attenuation (POL1) helped to reduce underestimation to the level of 17 % on average, but retrieval of N_0* (POL2) removed underestimation completely. This efficiency of the two polarmetric estimates were confirmed by the good values of Nash coefficient of 0.68 for POL1 and 0.73 for POL1 to be compared to 0.17 for CONV.

4.3 CONV vs. POL1 evaluation

The improvement of polarimetric measurements to correct for attenuation could be verified by comparing CONV and POL1. The data subset was larger because it also included cases of when snow was present in the radar beam. The errors caused by presence of bright band were corrected. Comparison pairs were stratified by the value of mean attenuation every 1 dB up to 4 dB and values higher then 4dB.

As the value of mean attenuation increased, CONV estimate was more and more biased with the respect to raingauges while bias for POL1 remained stable (see Fig 8). The improvement brought up by ZPHI algorithm by correcting reflectivity for attenuation was also evidenced by the behavior of Nash criterion value increasing for POL1 and decreasing for CONV and reaching for the mean attenuation bigger than 4 dB the value of 0.6 for POL1 and 0.1 for CONV.

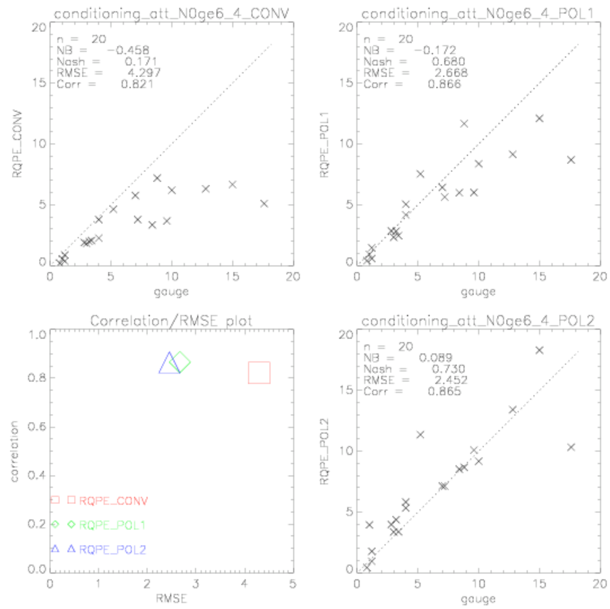

Fig. 7 Correlations plots and examined scores values for three radar estimates CONV, POL1 and POL2 versus raingauges measurements conditioned by absence of attenuation and and mean value of log(N_0*) greater then 6.4

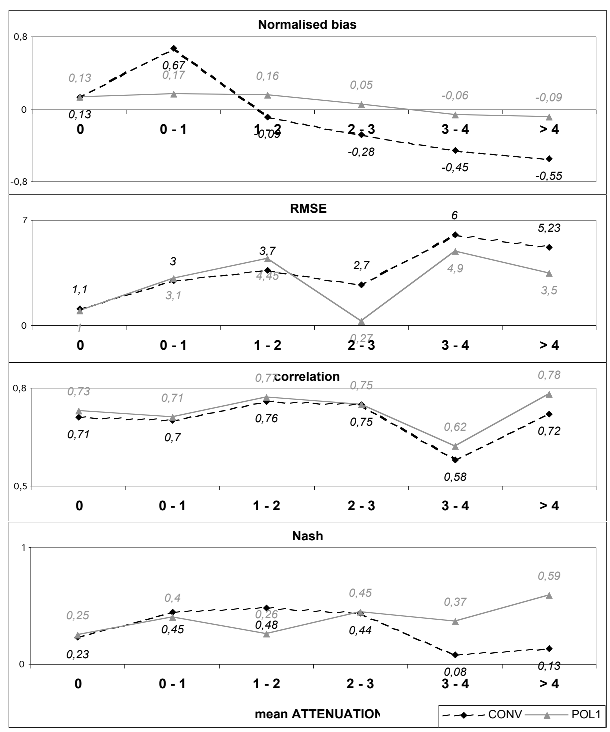

Fig 8 Scores on comparing CONV and POL2 for different level of attenuation

5. CONCLUSION

The validation methodology is quite original in the sense that a careful examination of the various error sources is done and the improvement of polarimetry is evaluated for each error type. Special emphasis was put on variation in drop size distribution and attenuation when the impact of other sources of errors like VPR effects, ground clutter, orogenic and non orogenic shielding was reduced to minimum.

The improvement introduced by polarimetry on rainfall measurements was especially evident for the convective situations and intense rain events characterized by strong attenuation. For these cases accuracy of evaluated polarimetric algorithm ZPHI reached remarkable level of 0.7 of Nash criterion. The results are yet not very robust due to sample size meeting this condition, but the multi-event data would be expended as the rain events would be recorded. For all other conditions prone to error in radar rainfall estimates like non-attenuated stratiform rain, attenuated stratiform rain or non-attenuated convective cells characterized by different then conventionally assumed DSD, the evaluated criteria indicated the positive enhancement for POL2 estimate. Even for the cases when improvement was not spectacular as there was no attenuation and the implicit DSD was close to the real one, polarimetric estimate was the one of the greatest correlation and value of Nash coefficient.

The improvement of polarimetric measurements processed by ZPHI algorithm to correct for attenuation could be documented by comparing CONV estimate with POL1 estimate. The improvement grown as the impact of attenuation increased.

The problem is the accuracy of retrieved N_0* values limited by the accuracy of estimating Δ_{DP}. This resulted in regularly observed ray-wise pattern of N_0* values caused by the inability to retrieve intercept parameter value as the differential phase shift along the ray is smaller then assumed threshold.

6. FUTUR WORK

The validation of polarimetry on rainfall estimation would be continue by evaluating other polarimetric algorithms and attenuation correction schemes, Already recorded, and continually upgraded multi-event data set would the base for comparative studies on different polarinmetric rainfall estimates as R(Zh, Zdr), R(KDP), $R(K_{dp}, Z_{dr})$.

7. ACKNOWLEDGEMENTS

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