“Testing of dual-polarization processing algorithms for radar rainfall estimation in tropical scenarios”

by

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1. ACRONIMS AND ABBREVIATIONS

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<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>QPE</td>
<td>Quantitative Precipitation Estimation</td>
</tr>
<tr>
<td>DSD</td>
<td>Rain Drops Size Distribution</td>
</tr>
<tr>
<td>VPR</td>
<td>Vertical Profile of Reflectivity</td>
</tr>
<tr>
<td>PPI</td>
<td>Plan Position Indicator</td>
</tr>
<tr>
<td>RHI</td>
<td>Range Height Indicator</td>
</tr>
<tr>
<td>VMI</td>
<td>Vertical Maximum Intensity</td>
</tr>
<tr>
<td>SRI</td>
<td>Surface Rainfall Intensity</td>
</tr>
<tr>
<td>SRT</td>
<td>Surface Rainfall Total accumulated</td>
</tr>
<tr>
<td>VCUT</td>
<td>Vertical Cut</td>
</tr>
<tr>
<td>LBM</td>
<td>Lowest Beam Map</td>
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</table>

2. ABSTRACT

The main objective of this work is to provide radar rainfall estimates for the validation of the H-SAF precipitation products in extra-European areas as part of the tasks of the incoming CDOP-3 phase. This is made possible by the availability of the data collected by mobile X-band polarimetric radar during the CHUVA project (Machado et al. 2014) held in Brazil, between 2011 and 2014. The field campaign provided the opportunity to test the quality of the retrieved X-band radar rainfall fields in tropical scenarios.

Generally speaking, quantitative precipitation estimation (QPE) using ground-based weather radar is affected by several uncertainty sources. Among these, the most important are the following: radar calibration, ground clutter, beam blockage, wet-radome attenuation, rain attenuation, beam-broadening, non-uniform beam filling, vertical variability of precipitation and WLAN interferences. At X-band, attenuation may generate detrimental effects in quantitative precipitation applications, especially in tropical scenario.

Different rainfall estimators, based on specific differential phase (Kdp) alone, on reflectivity (Zh) alone and in combination, are employed. Since the performance of the estimators depends on both the quality of the polarimetric variables and the applied polarimetric processing, the work describes the current polarimetric processing chain and the quality of the polarimetric variables used.

An optimized version of the data quality approach developed by the Italian Civil Protection Department (DPC) was implemented in this work, with the aim to evaluated the uncertainty related to the aforementioned error sources.

QPE results compared with rain gauge measurements, constituting an initial assessment of processing methodology, confirm the superiority of polarimetric algorithms as repeatedly reported in literature.
Rainfall is known to be highly variable, both in time and space. Traditional measurements by a network of rain gauges can provide accurate information of the rainfall only at their location. Radar, on the other hand, provides far better coverage in space and often also in time. With the development of technology, several S- and C-band radar networks have been upgraded from single to dual polarization and this has significantly increased the quality of the radar measurements. Furthermore, since X-band radars became available in the last decade have received the interest of scientific and operational communities. These radars present some characteristics that make them very attractive, especially in measurement campaigns: compact size, transportability and, generally, affordable costs are their main qualities.

However, a problem with radar systems measurements is the large number of error sources, which makes quantitative precipitation estimates based solely on radar difficult, unless these error sources are properly compensated.

Error sources that can be identified are: radar calibration, clutter, wet-radome attenuation, rain-induced attenuation, vertical profile of reflectivity (VPR), non-uniform beam filling. Despite this, polarimetric radars offer new variables that allow greater insight in precipitation and new ways to deal with these error sources (Bringi and Chandrasekar, 2001). In the following each of these error source will be briefly described.

Clutter results from the main beam or side lobes (partially) reflecting off the terrain or atmospheric objects (e.g., buildings or trees, airplanes, insects and birds). Close to the radar, ground clutter from objects can lead to overestimation of rainfall reflectivities. Another source of clutter results from atmospheric conditions bending the emitted radar beam towards the surface (i.e., anomalous propagation). This source of clutter can be highly variable in time, but its overall effect is generally limited.

Attenuation of the transmitted signal during a rainfall event can lead to strong underestimation of the rain rate. The amount of attenuation along the path of the transmitted signal is strongly dependent on the rain rate as well as on the transmitted wavelength. X-band radars are relatively inexpensive and easy to install, but suffer quite strongly from attenuation. Radars operating at longer wavelengths, like C-band and S-band radars, suffer less from attenuation. Correction for rain-induced attenuation was first proposed by Hitzfeld and Bordan (1954) and since then, other schemes have been developed.

Another source of attenuation is caused by precipitation on the radar radome, resulting in a liquid film of water. This film attenuates the signal (Bechini et al., 2010 and Schneebeli et al. 2012) and its effect becomes more pronounced during stronger precipitation intensities.

Vertical variations in precipitation as observed with radar give rise to the so-called vertical profile of reflectivity (VPR). The VPR-related uncertainties depend on vertical gradients of reflectivity and heights of the lowest and unblocked radar beams. They have an important impact on the measurement characteristics of the radar, even though close to the surface, the role of the VPR tends to be limited. For stratiform precipitation, the melting of snowflakes and ice crystals, aloft, results in relatively large droplets. Within this melting layer region, the returned radar signal intensifies (bright band), leading to an overestimation of the precipitation intensity, while measurements above the melting layer typically lead to an underestimation.

Non-uniform beam filling can also cause significant errors. This effect of course depends on the size of the radar measurement volume and the spatial heterogeneity of the rainfall. Because the relation between radar reflectivity and rainfall intensity is nonlinear and not unique (depending on the rain drops size distribution (DSD)), spatial rainfall variability within the radar measurement volume can cause errors.

Beam blockage is another error source and despite quantifiable and correctable to a given extent, affects the adopted scan strategy and the height of measurements above ground, especially in complex terrain scenarios.

WLAN interference is increasingly becoming an issue for weather radar measurements, especially in C-band where so far, the majority of the interference cases are reported. When another device is emitting microwaves at the same or nearby frequency as a weather radar, the radar may receive interference. Its measurements are disturbed and in the output images may manifest typical interference signatures such as dots, spokes, or stripes. In April 2011, the first field campaign of the CHUVA project took place in Fortaleza, on the northeastern coast of Brazil. Later other measurement campaigns, always within the CHUVA project, took place. In particular, the campaign of Vale do Paraíba held in December 2011, in the southern part of Brazil and the campaign of Manaus held in April 2014 in the north region, in the amazon rainforest, are carried out.
CHUVA (being the Portuguese word for rain, the acronym stands for Cloud processes of the main precipitation systems in Brazil: A contribution to cloud resolving modeling and to the GPM (Global Precipitation Measurement) aims at resolving microphysical processes that occur in tropical clouds in order to better understand formation of severe precipitation. This paper studies the possibilities of quantitative precipitation estimation (QPE) for a mobile polarimetric X-band weather radar operated by the Center for Weather Forecasting and Climate Studies (CPTEC) and the Brazilian Institute of Space Research (INPE).

This work, carried out within the HSAF visiting scientist activity, has to be intended as the integral part of the Federated Activity proposal (ref. HSAF_FA17_01), and is organized as follows: Sect. 4 describes the typical issues related to radar derived Quantitative Precipitation Estimates (QPE). Sect. 5 summarizes the data processing chain applied during the CHUVA campaign. In Sect. 6 another processing methodology is proposed with objective to verify the robustness of the radar rainfall algorithms currently implemented and used during the CHUVA field campaign. In Sect. 7, as assessment of the processing methodology, QPE results are evaluated against rain-gauges, performed hourly. In Sect. 8, a sensitivity analysis to data quality is introduced with the purpose to investigate the influence of different quality indexes associated to the radar precipitation, on raingauges comparison.

4. ISSUES ON RADAR QPE

To date, the most commonly used method to obtain a Quantitative Precipitation Estimation (QPE) is based on the inversion of the power law relating the rainfall rate (R), at ground level, to the radar reflectivity factor (Z):

\[ R = aZ^b. \]  

(1)

The Marshall–Palmer equation (Marshall et al., 1948) with \( a=200 \) and \( b=1.6 \) is generally assumed to be representative of stratiform precipitation. Other \( Z-R \) relations have been derived as well, more suitable during different types of precipitation and for other locations and this is indicative of how the inversion can be challenging because the rain is highly variable.

Dual polarization weather radars provide significantly more information about the observed scan volume than conventional weather radars. This additional information improves the dynamic processing of radar returns leading to more accurate QPE.

Several forms of rainfall algorithms can be developed depending on the polarimetric radar variables measurements used in the estimation: reflectivity (Z), differential reflectivity (\( Z_{DR} \)), specific differential phase (\( K_{DP} \)). Such models are mainly deterministic and derived from curve fitting, obtained by surface disdrometers, from which both Z and R can be inferred, or empirical interpretations. They are still based mainly on a power-law relation that apply to different bands, times and regions.

As mentioned in introduction, meteorological radar measurements are affected by several error sources: some are specific of the system (e.g., the calibration bias) and the adopted frequency band, some others are related to external factors (e.g., ground clutter, anomalous propagations, wet-radar attenuation).

In case of system miscalibration, the so-called radar “constant” \( C \), relating the reflectivity factor to the signal-to-noise ratio (SNR) at a given range distance \( r \) via the following expression (Doviak and Zrnic, 1993):

\[ Z = C r^2 \text{SNR}. \]  

(2)

has to be estimated.

The determination of \( C \) is usually denoted as radar calibration. Radar systems can be calibrated indirectly by measurements of individual system parameters, externally using point targets or by comparison with other (reference) reflectivity profiles. Radars with a scanning antenna can apply the external calibration by measuring the return signal from a defined reflector of known cross section. Conventionally, absolute calibration is done using a test sphere suspended below a balloon, receiving the signal transmitted by a standard horn or using the
Sun as a standard source. External methods are not ever applicable for all radar systems. For vertical pointing radars with a fixed antenna and narrow beam width (large apertures) calibration using corner reflectors is a difficult task. Therefore, the indirect method (named also as budget calibration) is still the standard for many weather radars. The calibration error can be minimized through a close monitoring and vigorous hardware maintenance of the radar system.

In addition to the reflectivity offset, for the polarimetric systems, $Z_{DR}$ can also be biased. This offset is determined by the difference between the H- and the V-channel in dual polarization radars. Traditionally, it is compensated by pointing the antenna in the vertical direction and rotating it for any azimuthal angle (Gorgucci et al., 1999). Since raindrops look like isotropic scatterers at vertical incidence, signal returns should exhibit similar behavior independently by the polarization state. Consequently, any deviation of $Z_{DR}$ from zero can be directly attributed to the system bias. The $Z_{DR}$ offset, estimated by averaging the samples collected at vertical incidence in light precipitation conditions in case of negligible wet-radome conditions, can be subtracted from the measured $Z_{DR}$.

Any contamination of the radar signal by non-precipitation echoes, including returns from ground, is normally referred as Clutter. It appears in areas where the radar beam intercepts the Earth's surface, or any non-meteorological target such as buildings, trees, airplanes, insects, birds, etc. Clutter signal may be much more intense than the strongest meteorological signal and, in some cases, may even saturate the receiver. Strong Clutter returns coming, for example, by the reflections of the main lobe of the beam on the mountain slopes: can be removed by imposing a threshold on the minimum height to validate the measures. Other techniques rely on the fact that the ground clutter is essentially stationary, so that it is possible to eliminate all those echoes that have the radial component of velocity near zero. This could, however, eliminate part of the echoes due to rain moving orthogonally with respect to the radial direction and, therefore, should be used together with additional information such as the static clutter map (CMAP). It is a volumetric reflectivity map obtained by averaging reflectivity measurements collected in clear-air conditions.

It is worth noting that CMAP is dependent on the propagation conditions depending on atmospheric temperature and humidity, so that it should be updated at least on a seasonal basis.

Among the main causes of errors in meteorological radar observation there is the attenuation along the path of the signal transmitted during a rainfall event. It is strongly dependent on the rain rate, is important at C-band, becoming relevant at X-band, because the absorption cross section is inversely proportional to the wavelength. According to Hitschfeld and Bordan (1954), the measured reflectivity factor at a given range $r$ for an attenuating wavelength, can be expressed as

$$Z_m(r) = Z_c(r) \delta C A(r)$$  \hspace{1cm} (3)

where $Z_c(r)$ is the intrinsic equivalent reflectivity factor at the same range, $\delta C$ represents a potential radar calibration error, and $A(r)$, often referred as Path Integrated Attenuation PIA (dB), is defined as twice the integral of $k$ between range 0 and range $r$.

$$A(r) = A(r_0) \exp \left[ -0.46 \int_{r_0}^{r} k(s) ds \right]$$  \hspace{1cm} (4)

$k$ is the specific attenuation (dB km$^{-1}$), depending on the radar wavelength, the size distribution and temperature of the raindrops. The variable $r_0$ represents the range where the reflectivity sampling is started or where the reflectivities can be considered as free of noise. Here, $A(r_0)$, hence enables a description of attenuation effects occurring in case of rain in the vicinity of and at the radar site (e.g., radome attenuation).

Hitschfeld and Bordan, further emphasized “the difficulties associated with quantitative work at the shorter wavelengths,” due to the instability of the solution and, in particular, its strong sensitivity to radar calibration errors (Delrieu et al. 1999).

Considerable work has been dedicated in recent years to the development of observation techniques and processing algorithms aimed at the retrieval of rainrate profiles from attenuated radar measurements. In this way, single-frequency techniques making use of surface returns for the PIA estimation, as well as dual-frequency and dual-beam techniques, have been proposed to circumvent the difficulties posed by the attenuation equation (Testud et al. 2000; Bringi and Chandrasekar, 2001).
During the CHUVA campaign, held in Brazil between 2011 and 2014, an X-band polarimetric radar, manufactured by Gematronik, Germany, has been employed (Fig. 1). Its main characteristics are showed in table 1.

<table>
<thead>
<tr>
<th>METEOR 50-DX</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter</td>
<td>Magnetron with 35 kW per channel</td>
</tr>
<tr>
<td>Polarization type</td>
<td>Simultaneous horizontal and vertical transmission.</td>
</tr>
<tr>
<td>Pulse width</td>
<td>0.5 μs</td>
</tr>
<tr>
<td>Operative PRF</td>
<td>1500 Hz</td>
</tr>
<tr>
<td>Antenna</td>
<td>1.8 m diameter, 1.3° beam width</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>43 dB</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>9.375 GHz</td>
</tr>
<tr>
<td>Scanning protocol</td>
<td>Combination of RHI and volume scans.</td>
</tr>
<tr>
<td>Elevation angles</td>
<td>1.8°, 3°, 4.1°, 5.3°, 6.4°, 7.5°, 8.8°, 10.2°, 11.9°, 13.8°, 16.1°, 18.6°, 21.4°</td>
</tr>
<tr>
<td>Elevations number</td>
<td>13</td>
</tr>
<tr>
<td>Angolar resolution</td>
<td>1 deg</td>
</tr>
<tr>
<td>Range resolution</td>
<td>150 m</td>
</tr>
<tr>
<td>Max distance</td>
<td>100 km</td>
</tr>
</tbody>
</table>

Table 1. Main technical specifications of the radar system

Figure 1. Radar Meteor 50DX with radome and without radome mounted.

The radar provides the standard polarimetric observables: reflectivity in horizontal polarization ($Z_h$ [dBZ]), differential reflectivity ($Z_{DR}$ [dB]), differential phase shift ($\Psi_{dp}$ [deg]), specific differential phase shift ($K_{dp}$ [deg km$^{-1}$]), copolar correlation coefficient ($\rho_{hv}$ [-]), as well as the Doppler velocity ($v_D$ [m s$^{-1}$]) and velocity spectrum width ($\sigma_{vD}$ [m s$^{-1}$]).

Below are briefly described the main steps of the processing chain, adopted during this measurements campaign, to remove or compensate the principal error sources.

The adopted scan strategy includes 13 elevations from 1.8° to 21.4°. The lowest elevation was chosen at 1.8° to prevent the complete blocking of the signal and therefore to minimize the interference from clutter at higher elevations.

To minimize interference from Clutter was set a minimum threshold of height for the validation of the measures (1.8°) and employed a threshold (1.44 ms$^{-1}$) on the Doppler velocity $v_D$. This however leads to remove those precipitations having radial doppler velocity near zero.

The Radar reflectivity was calibrated by comparing the reflectivities inferred by a disdrometer located about 20 km from the radar with its reflectivities measured above the location of the disdrometer using an elevation of 2.5 degree. The comparison was restricted to those events where the radar site was outside of the rainy cell and then its radome was dry. In addition, to limit the effects of rain attenuation to max 2 dB, a further limit was imposed.
by taking into account those events which showed a maximum variation of 10 degrees in the differential phase shift $\Psi_{dp}$. After the comparison, a calibration offset of 6.5 dB was determined (Schneebeli et al., 2012). The correction of bias in $Z_{DR}$ was obtained by pointing the antenna in vertical direction and mediating the measurements across 110 full azimuthal cycles. At the end of procedure, a bias of -0.34 dB was found.

Regarding rain attenuation correction, two different schemes were adopted: the ZPHI algorithm from Testud et al. (2000) and the extended Kalman filter (EKF) from Schneebeli and Berne (2012).

ZPHI method calculate the attenuation as:

$$A_h(i) = \frac{Z_h(i)^b}{I(0,i_1) + (10^{0.1b\Delta \Phi_{dp}} - 1) I(i,i_1)} (10^{0.1b\Delta \Phi_{dp}} - 1)$$

where $A_h$ (dB km$^{-1}$) is the specific one-way attenuation

$$A_{dp} = \alpha A_h^\beta$$

with

$$I(i, i_1) = 0.46b \sum_{j=1}^{i_1} Z_h(j)^b \Delta r$$

where $i_1$ is the last bin in the range profile and $\Delta \Phi_{dp}$ is the differential phase from 0 to $i_1$. ZPHI performance depends on the accuracy estimation of $b, \beta, \alpha$ and $\gamma$ parameters whose numerical values are given in Table 2.

<table>
<thead>
<tr>
<th>$b$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.724</td>
<td>0.117</td>
<td>1.265</td>
<td>0.212</td>
</tr>
</tbody>
</table>

Table 2. Parameters for the ZPHI method

There parameters were calculated with the T-matrix modeling method (Barber and Yeh, 1976) from the DSD measurements provided by a disdrometer.

The EKF method employs relations between different polarimetric moments, between a range bin and the next one, to compensate radar measurements for attenuation caused by rain in medium conditions. The basic principle behind the EKF method is that the different polarimetric moments can be estimated in various ways. An example of how the method works is given by estimation of $K_{DR}$, the latter can be estimated differentiating $\Phi_{dp}$ or exploiting the direct relationship with the $Z_h$. For both ways of estimation are associated uncertainties which are used in the EKF method to weight the results of the estimates. Relations between polarimetric moments are calculated with measurements carried out through disdrometer and consequent T-matrix modeling of the parameters.

$$\Psi_{dp}(i) = -2 \Delta r 10^{R_{dp}(i)/10} + \Phi_{dp}'(i) + \delta_{hv}(i)$$

$$\Psi_{dp}(i + 1) = 2 \Delta r 10^{R_{dp}(i)/10} + \Phi_{dp}(i) + \delta_{hv}(i)$$

$$Z_h^m(i) = -\mu_h \Phi_{dp}(i) + Z_h(i)$$

$$Z_v^m(i) = -\mu_v \Phi_{dp}(i) + Z_v(i)$$

$$-\kappa_h(i) = -\lambda_h R_{dp}(i) - Z_h(i)$$

$$-\kappa_v(i) = -\lambda_v R_{dp}(i) - Z_v(i)$$

$$0 = \zeta (Z_h(i) - Z_v(i))^{\eta} - \delta_{hv}(i)$$

$$0 = \Phi_{dp}'(i) - \Phi_{dp}(i) - 2 \Delta r 10^{R_{dp}(i)/10}.$$
was introduced the notation $\Phi_{dp}(i) = \Phi_{dp}(i + 1)$ and assumed $\delta_{hv}(i + 1) \approx \delta_{hv}(i)$. Others numerical values are given below in Table 3.

<table>
<thead>
<tr>
<th>$\mu_h$</th>
<th>$\mu_v$</th>
<th>$\kappa_h$</th>
<th>$\kappa_v$</th>
<th>$\lambda_h$</th>
<th>$\lambda_v$</th>
<th>$\zeta$</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.212</td>
<td>0.119</td>
<td>44.03</td>
<td>42.35</td>
<td>1.283</td>
<td>1.176</td>
<td>0.670</td>
<td>1.612</td>
</tr>
</tbody>
</table>

**Table 3.** Parameters for the EKF method

It is worth mentioning that the parameters obtained are optimized to the disdrometer representation (not always available) and related to the period and to the location where the measurements were carried out. In addition to rain-induced attenuation, other sources of error can be corrected using the EKF algorithm: for example, the wet-radome attenuation. One of the advantages of EKF is that calculates $K_{DP}$ and $\phi_{dp}$ with different reflectivity offsets and can be compared along the ray path. The comparison that exhibits the smallest absolute bias determines the reflectivity offset.

The offset obtained is, however, dependent on both the angle of elevation and azimuth, with values ranging between 10 and 13.5 dB. Variability that is related to non-uniform way in which the radome is wet.

Finally, after reflectivity offset and wet-radome attenuation was determined and the rain attenuation corrected for $Z_{dr}$ and $Z_{hi}$ as well, then was adopted the average of the following power law relations to estimate the rain rate:

\[ R = 15.813K_{DP}^{0.774} \]  \hspace{1cm} (16)
\[ Z_h = 214.18R^{1.636} \]  \hspace{1cm} (17)

where $R$ is rainfall rate in mm h$^{-1}$ units, $K_{DP}$ in deg km$^{-1}$ and $Z_h$ in mm$^6$m$^{-3}$.

## 6. PROPOSED PROCESSING METHODOLOGY

In this work, the processing chain methodology adopted during the measurement campaign CHUVA is integrated by introducing other algorithms including the characterization of the data quality. The objective is to develop a robust and efficient radar QPE processing chain, evaluate and optimize the algorithms in the light of the recent advancement in the field.

The proposed scheme is finalized to compensating or at least to identifying the most common error sources, eliminating or minimizing the contaminations. Among them, the following error sources are considered: contamination from non-precipitation echoes (clutter), Partial Beam Blocking (PBB), beam broadening at increasing distances, vertical variability of rain distribution and rain induced attenuation (Bringi and Chandrasekar, 2001).

Moreover, a quality indicator for each source of error it is introduced through appropriate tests, allowing, when possible, its use to compensate for the polarimetric variables. These quality matrices constitute partial indexes that will then be part of an overall data quality indicator. If one of the input variables, after data quality procedure, results to not satisfy a predefined quality standard, it is flagged as no quality data and thus discarded or corrected. The data quality is based on several tests and procedure (figure 2) described in the next pages.
The main steps of data correction and quality indexes within the proposed processing chain can be summarized as follows:

**GROUND CLUTTER**

The raw volumetric data is filtered from non-precipitation echoes which include ground clutter; biological returns from birds, bats, and insects; electronic interferences; and chaff. This filtering technique is based on a fuzzy logic approach (Vulpiani et al., 2012) where are considered as input, a static clutter map (CMAP), radial velocity (V), differential reflectivity (Z<sub>dr</sub>), co-polar correlation coefficient (ρ<sub>hv</sub>) and differential phase shift (ϕ<sub>dp</sub>). For each quality indicator X<sub>j</sub> (i.e., X<sub>1</sub> = CMAP, X<sub>2</sub> = V, X<sub>3</sub> = Z<sub>dr</sub>, X<sub>4</sub> = ρ<sub>hv</sub>, and X<sub>5</sub> = ϕ<sub>dp</sub>), the degree of membership in the non-meteorological target class is defined through a trapezoidal transformation function d<sub>j</sub> = d(X<sub>j</sub>):

\[
d_j = \begin{cases} 
0 & \text{if } X_j < X_{1,j} \text{ or } X_j > X_{4,j} \\
(X_j - X_{1,j})/(X_{2,j} - X_{1,j}) & \text{if } X_{1,j} < X_j < X_{2,j} \\
(X_{4,j} - X_j)/(X_{4,j} - X_{3,j}) & \text{if } X_{3,j} < X_j < X_{4,j} \\
1 & \text{if } X_{2,j} < X_j < X_{3,j} 
\end{cases}
\]

where X<sub>i,j</sub> is the i<sup>th</sup> vertex of the trapezoid relative to the j<sup>th</sup> quality indicators as shown in figure 3.

The output is a fuzzy variable expressing the degree of membership d to the class non-precipitation echoes. The complementary q<sub>j</sub> = 1 - d<sub>j</sub> can be defined as the quality of the measurement and clutter quality index is obtained through a weighted sum of the relative quality indices.

\[
q_{\text{clutter}} = \frac{\sum w_j q_j}{\sum w_j}
\]

This quality indicator is employed to identify Clutter: when the quality is low (i.e. q<sub>clutter</sub> < 0.6) the datum is rejected. The parametrization used for defining q<sub>clutter</sub> is shown in Table 4.
Table 4. Parameters applied for clutter determination.

<table>
<thead>
<tr>
<th>$X_j$</th>
<th>$w$</th>
<th>$X_{1,j}$</th>
<th>$X_{2,j}$</th>
<th>$X_{3,j}$</th>
<th>$X_{4,j}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMAP</td>
<td>0.5</td>
<td>10</td>
<td>30</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>V</td>
<td>0.3</td>
<td>-0.2</td>
<td>-0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>$Z_{dr}$</td>
<td>0.4</td>
<td>0.7</td>
<td>1.0</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$\rho_{hv}$</td>
<td>0.4</td>
<td>0.1</td>
<td>0.15</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$\phi_{dp}$</td>
<td>0.4</td>
<td>15</td>
<td>20</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

Ground and WLAN interference have been removed using a statistical filter. It is an iterative filter consisting of the combination of entropy function, texture filter and median filter. In order to assess the need for the application of the declutter filter or its application only where needed, an entropy function is used. The entropy is defined as the average information contained in any given message; it is applied to a binary Boolean map $x$ obtained placing 1 to all values of the reflectivity map greater than a threshold $t_e$, ($t_e=0$), namely:

$$H(x) = -\sum_k p_k \log_2 p_k$$  \hspace{1cm} (20)

where $p_k$ is the probability distribution that event $x$ happens obtained with a normalized histogram. If the entropy $H$ exceeds the threshold of 0.0005, the declutter filter is applied.

Next step is the iterative application of the median filter and texture filter which exploits the textural spatial correlation of meteorological targets with respect to artifacts. The entropy function detects the pixels affected by clutter and the median filter is applied only in those pixels, leaving unaltered the field without clutter. The texture is applied in a similar way.

The texture of radar signatures is also used to verify the spatial self-consistency. The texture function ($Tex$) is a spatial root mean square function, defined over a box of $N\times N$ contiguous pixels as:

$$Tex_N(x) = \frac{1}{N^2} \sum_{n=-N/2}^{N/2} \sum_{n=-N/2}^{N/2} [x(n) - x(0)]^2$$  \hspace{1cm} (21)

where $x$ is a generic radar observables ($Z_{hh}$ in such case) and $x(0)$ is the box center. The $Tex$ function is also used as a clutter removal tool such that a mask is introduced as follows:

$$Tex_N(x) \leq t_{threshold}(x)$$  \hspace{1cm} (22)

where $t_{threshold}$ is an ad hoc threshold defined to identify the meteorological target with respect to environmental and artificial clutter, to be tuned on the final radar system features.

Figure 4 shows examples of clutter correction applied to an event occurred on April 24, 2011, observed by the radar located in Fortaleza and an event occurred on December 1, 2011, observed by the radar located in São José dos Campos (Vale do Paraiba campaign).
Figure 4. PPI, at lower elevation angle, of reflectivity raw (left panel) and filtered to remove the clutter (right panel) in Fortaleza campaign (top panels) and Vale do Paraíba campaign (bottom panel).

Ground clutter shows up more evident near the radar site since the radar beam trajectory takes it from close to the surface at the radar site. Thus, most ground cluttering matter will be relatively close to ground level, and a ring of ground clutter objects can show up near the radar site. You can also spot ground clutter by viewing a loop of individual radar pictures and looking for stationary radar returns embedded with moving radar returns. The statistical filter was able to remove the clutter near the radar. It was also removed the ray to the north probably caused by an interference and the stationary ground clutter target situated at near 30 km and 240° of azimuth due to ground morphology.

BEAM BLOCKING

When the radar beam intercepts an obstruction, two situations are possible: 1) only part of the beam cross section illuminates the intercepted topography (partial blockage), or 2) the radar beam is completely blocked (total blockage). We know that for the best estimate of the precipitation we have to use the lowest possible elevation angles, but it is precisely for these angles that the beam blocking phenomenon is more present. According to Bech et al. (2003), the percentage area of the radar beam cross section blocked by topography may be expressed as a function of the radius of the beam cross section $a$ and the difference of the average height of the terrain and the center of the radar beam $y$ (see figure 5). Depending on the relative position of the beam height respect to topography, $y$ may be either positive or negative.
Figure 5. Elements considered in the radar beam blockage function: \( a \) is the radius of the radar beam cross section, \( y \) the difference between the center of the radar beam and the topography.

According to these definitions, partial beam blockage occurs when \(-a < y < a\), total beam blockage means that \( y \geq a \) and, finally, \( y \leq -a \) implies there is no blockage at all. Using the notation introduced above, it can be seen that partial beam blockage (PBB) may be written as

\[
PBB = \frac{y\sqrt{a^2 - y^2} + a^2\arcsin\frac{y}{a} + \frac{\pi a^2}{2}}{\pi a^2}
\]  

On the other hand, the height of the center of the radar beam \( h \) is given at a distance \( r \) by the expression (Doviak and Zrnic, 1993)

\[
h = y\sqrt{r^2 + (k_e R)^2 + 2k_e R \sin \theta} - k_e R + H_0
\]

where \( R \) is the earth’s radius, \( k_e \) is the ratio between \( R \) and the equivalent earth’s radius, \( \theta \) is the antenna elevation angle, and \( H_0 \) is the antenna height. The usual value for \( k_e \) in the first kilometer of the troposphere, assuming to be in standard atmosphere, is approximately 4/3.

The occultation rate PPIs (denoted by eq. 23 and expressed in values ranging from 0 up to 1) is then be used to correct the radar reflectivity on a pixel-by-pixel basis. Under the assumption that the radar reflectivity does not vary with height within the radar beam, the correction factor \( \alpha(i, j) \) to be applied to the observed reflectivity (mm$^6$m$^{-3}$) read

\[
\alpha(i, j) = \frac{1}{1 - PBB(i, j)}
\]  

where \( i \) and \( j \) are the pixels coordinates, in azimuth and range, whose PBB values are between 0.1 and 0.7 as in Tabary (2007). The reflectivity corrected \( Z_h'(r) \) is then

\[
Z_h'(i, j) = Z_h(i, j) \cdot \alpha(i, j)
\]

The quality associated with the beam blocking can then be expressed as the complementary of the PBB:

\[
q_{PBB} = 1 - PBB
\]  

A quality of measurement burdened by beam blockage dramatically decreases. The quality index \( q_{PBB} \) of bins where the radar beam might be compensated is expressed by the formula:
\[ q_{PBB} = \begin{cases} 1 & \text{for PBB < 0.7} \\ 1 - PBB & \text{for PBB > 0.7} \end{cases} \] (28)

where the threshold is set as 0.7, as in Tabary (2007).

A map that indicates, for each pixel of the radar volume, to what extent terrain obstacles are visible from the radar is called a radar visibility map. The visibility, complementary of the PBB, is calculated ray by ray by combining the scan geometry of the radar, a digital terrain model (DEM), and the earth’s curvature (eq. 24).

It can be a simple binary map, indicating "visible" or "nonvisible", or it can be a more precise estimate indicating the visibility as a percentage ranging from 0% visible up to 100% visible.

Figures 6a and 6b depict examples of the visibility map obtained at the lowest elevation angle. Any region not covered by the color indicates a complete visibility while different levels of shading correspond to the partial visibility.

**Figure 6a.** Map of radar visibility in Fortaleza site (black, no visibility and white, full visibility) for the lowest elevation (left panel) and profile of the beam (right panel), PBB and DEM along a given azimuth (247 degrees). Maximum range is 100 km.

In the beam profile of figure 6a, in Fortaleza site, along the azimuth of 247 degrees, it is shown how the ground intercepts the beam of just over 20%. In other directions obstruction is less.
**Figure 6b.** Map of radar visibility in São José dos Campos site (black, no visibility and white, full visibility) for the lowest elevation (left panel) and profile of the beam (right panel), PBB and DEM along a given azimuth (330 degrees). Maximum range is 100 km.

The region around the radar site in Vale do Paraiba is characterized by mountainous areas with very high peaks (over 2000 m). In the beam profile of figure 6b, in São José dos Campos site, along the azimuth of 330 degrees, is shown how the ground intercepts the beam of over 80%. In some directions the obstruction is less while in others have the full blocking of the beam.

Resuming, for two practical reasons, we are interested in the visibility map:

1. For further data processing, it is crucial to know whether a pixel is (a) perfectly visible, (b) completely shielded and thus missing, or (c) frequently contaminated by clutter or partially shielded and thus less accurate and less reliable. Pixels of different visibility have to be treated in different ways, for instance, when generating ground level precipitation maps ($q_{PBB}$).
2. The bias in partially visible regions is corrected if there is a good estimate of the visibility.

**RANGE DISTANCE**

The quality of radar data decreases with increasing distance from the radar, either because the beam broadens with the distance; the measurement comes from a larger volume and related averaging errors increase as well, or for the increasing height with respect to terrain. There is no possibility of correcting this effect. However, the data range-related deterioration can be determined quantitatively and taken into account in the related quality index. Following the approach proposed by Friedrich et al. (2006), but introducing a square root, it can be evaluated using a non-linear function, as in Rinollo et al. (2013) and repeated as follows:

$$ q_{distance} = \begin{cases} 0.5 & \text{for } r \geq r_{\text{max}} \\ 1 & \text{for } r \leq r_{\text{min}} \\ \frac{r_{\text{max}} - r}{r_{\text{max}} - r_{\text{min}}} & \text{for } r_{\text{min}} < r < r_{\text{max}} \end{cases} $$

(29)

where $r_{\text{max}}$ can be set to 100 km and $r_{\text{min}} = \Delta r/2$ ($\Delta r$ is the radar range resolution). The square root is introduced in order to ensure that quality does not drop too fast with the range distance.

The Eq. (29) is represented in Figure 7, showing both the polar map of the distance quality index and its profile along a given azimuth.
VERTICAL VARIABILITY

To mitigate radar precipitation errors due to non-uniform vertical profiles of reflectivity (VPR), and also due to the presence of the bright band, during stratiform precipitation, which causes significant overestimation in radar precipitation estimates, an appropriate correction should be applied. The most important parameter that defines the vertical profile of reflectivity is the height of the freezing level. This value determines the position of the melting layer where, in polarimetric radar, the vertical profiles of $Z_h$ return intensified, exhibiting well-pronounced maxima, while in $\rho_{HV}$ presents the minimum. This can be explained by the fact that $Z_h$ depends on concentration of melting ice whereas $\rho_{HV}$ measurements do not. Therefore, the identification of the melting layer is important not only for the VPR correction but it is also aimed at appraising the limit in distance or the height at which occurs for the rain attenuation correction.

The height of the freezing level is obtained from the vertical temperature profiles, derived from the measurements of a surface-based passive microwave radiometer profiler (MP3000) located near the radar site. The profiles are derived from measurements of absolute microwave radiance (expressed as “brightness temperature”) at 35 frequencies in the range of 22-30 GHz and 51-59 GHz.

As a result of the storm vertical variability, the radar observations made at relatively high altitudes are not representative when estimating precipitation at ground level. In order to deal with such an issue, the reflectivity field can be projected onto the surface by estimating the vertical profile of reflectivity. Thus, after correction for VPR, the associated quality is assumed equal to 1. In case the compensation of this effect is not introduced in the radar data, the quality index associated to VPR can be estimated as in Friedrich et al. (2006):

$$ q_{VPR} = \begin{cases} 
\frac{h_{+3dB} - h_{FL+200}}{2(h_{+3dB} - h_{-3dB})} & \text{for } h_{-3dB} < h_{FL+200} \text{ and } h_{+3dB} > h_{FL+200} \text{ and } h_{-3dB} > h_{FL-500} \\
0.5 & \text{for } h_{-3dB} \geq h_{FL+200} \\
1 & \text{for } h_{+3dB} \leq h_{FL-500} \text{ and } h_{+3dB} < h_{FL+200} \\
0 & \text{for } h_{-3dB} > h_{FL-500} \text{ and } h_{+3dB} < h_{FL+200} \\
\frac{h_{-3dB} - h_{FL-500}}{2(h_{-3dB} - h_{+3dB})} & \text{for } h_{-3dB} < h_{FL-500} \text{ and } h_{+3dB} > h_{FL-500} 
\end{cases} $$

(30)

where $h_{FL}$ is the freezing layer height, $h_{+3dB} = h_{beam} + \delta_{up}$, $h_{-3dB} = h_{beam} - \delta_{dn}$, $\delta_{up} = r \sin(\phi)/\sin(\gamma+\phi)$, $\delta_{dn} = r \sin(\phi)/\sin(\gamma-\phi)$, $\phi = 0.5\Phi_{3dB}$ and $\gamma = \arctan((R+H_0)\cos(\theta))/(r+(R+H_0)\sin(\theta))$, and with $\Phi_{3dB}$ being the 3 dB beam width and $\theta$ the antenna elevation. $h_{beam}$ is the beam height defined in Eq. (24).

Figure 8 shows a representation of the eq. (30) with the polar map and its profile along a given azimuth at 4.1° elevation level. The Vertical Quality Index decreases significantly when it crosses the melting layer region, where
the exterior of the ice crystals develops a water coating, and precipitation and ice crystals coexist. The index then rises slightly when it reaches and exceeds the freezing level.

**Figure 8.** Vertical Quality index polar map at 4.1° elevation (left panel) and its profile along a given azimuth (right panel). FL indicate the height of the freezing level (5.42 km).

### DIFFERENTIAL PHASE PROCESSING

A polarimetric radar system provides measurements of the total differential phase \( \Psi_{dp} \) that is the sum of the differential propagation \( \Phi_{dp} \) and the backscatter phase \( \delta_{hv} \). We are only interested in the propagation component for attenuation correction and for rainfall estimation purposes, being \( K_{dp} \) related to the range derivative of \( \Phi_{dp} \). Furthermore, \( \Psi_{dp} \) is also conditioned by system noise, offset, and potential aliasing problems.

An Iterative moving-window range Finite Derivative scheme (IFD) proposed by Vulpiani et al. (2012), also used in order to minimize the number of outliers (Besic et al. 2016), is applied to the differential phase measured \( \Psi_{dp} \) and can be summarized through the following few steps (see flow chart of Figure 9):

1) Pre-filtering. Phase is smoothed by applying a 2-D median filter to delete strong phase variations.

2) \( K_{dp} \) retrieval. A first guess of the specific differential phase \( K'_{dp} \) is retrieved from the raw differential phase \( \Psi_{dp} \) through a finite-difference scheme over a given sized moving window \( L \).

   \[
   K'_{dp} \approx \frac{1}{2} \frac{\Psi_{dp}(r_k + \frac{L}{2}) - \Psi_{dp}(r_k - \frac{L}{2})}{L} \tag{31}
   \]

3) \( K_{dp} \) check. The out-of-range \( K_{dp} \) values are nullified. \( K_{dp} \) typically ranging between -2 deg km\(^{-1}\) (as for vertically oriented ice crystals) and 20 deg km\(^{-1}\) (as for heavy rain).

4) \( \Phi_{dp} \) reconstruction. The filtered differential phase is estimated as

   \[
   \tilde{\Phi}_{dp}(r) = 2 \int_{0}^{r} K'_{dp}(s) \, ds \tag{32}
   \]

5) \( K_{dp} \) retrieval (final guess). The final estimation of the specific differential phase \( K_{dp} \) is then obtained as a range derivative of the reconstructed \( \tilde{\Phi}_{dp} \).

Steps (3)–(4) are repeated iteratively to reduce the expected \( K_{dp} \) standard deviation \( \sigma_{K_{dp}} \). According to the uncertainty propagation theory, the standard deviation of the final \( K_{dp} \) can be expressed (Vulpiani et al., 2012) as
\[ \sigma (K_{dp}^{(i)}) = \frac{1}{\sqrt{2N^l}} \sigma (\Psi_{dp}) \]

where \( N \) is the number of range gates contained in the L-sized moving window (i.e., \( N = L/\Delta r, \Delta r \) being the range resolution), and \( I \) is the number of iterations (with \( I \geq 1 \)). It is worth mentioning that the retrieved differential phase is not affected by the system offset, which is removed through the derivative computation. This feature is particularly useful for attenuation correction purposes based on differential phase shift measurements.

\[ \Phi_{dpm} \]

**Pre-filtering**

• Phase smoothed by applying a 2-D median filter

\[ \Phi_{dpf} \]

**Kdp retrieval**

• Kdp is estimated as the range derivative of the filtered Phidp using a given sized moving window L

\[ K_{dp} \]

**\( \Phi_{dp} \) reconstruction**

• \( K_{dp} \) check
• \( \Phi_{dp} \) reconstruction as the range integral of the estimated Kdp

This scheme has already demonstrated its potential in reconstructing the differential phase \( \Phi_{dp} \) and in retrieving the specific phase \( K_{dp} \) in tropical areas like the Philippines (Crisologo et al. 2014), where it has been implemented in the open source libraries of data processing software (Heistermann et al. 2013).

The figures 10a and 10b show examples of differential phase range profiles: raw (blue line) and filtered (red line). They are observed by the radar located in Fortaleza during a convective event occurred on April 26, 2011 at 9:26 UTC (10a, left panel) and a stratiform event occurred on April 18, 2011 at 16:12 UTC (10a, right panel). In figure 10b are shown convective events observed respectively by the radar located in Manaus on February 21, 2014 at 8:50 UTC (10b, left panel) and by the radar located in Sao José dos Campos on November 13, 2011 at 22:06 UTC (10b, right panel).

To better evaluate the effect of the filtering approach, the current system offset has also been subtracted to the raw \( \Phi_{dp} \) (see the blue curve). The bottom panel in figures 10a and 10b show the corresponding retrieved specific differential phase.

In the following range profiles, the direction of the maximum value (the degree of azimuth, within the PPI, where the reflectivity is highest), and the direction of the maximum number of bins (the degree of azimuth where the beam contains the largest number of data) have been selected.
Figure 10a. Examples of observed and filtered $\Phi_{dp}$ range profiles and the estimated $K_{dp}$ along the direction of max value (left panel) and of max number of bins (right panel) for events, observed by the radar located in Fortaleza, occurred respectively on April 26, 2011 at 9:26 UTC (left) and on April 18, 2011 at 16:12 UTC (right).

Figure 10b. Examples of observed and filtered $\Phi_{dp}$ range profiles and the estimated $K_{dp}$ along the direction of max value for events, observed by the radar located in Manaus, on February 21, 2014 at 8:50 UTC (left panel) and by the radar located in São José dos Campos, on November 13, 2011 at 22:06 UTC (right panel).

The quality index associated with the specific phase $K_{dp}$ can be defined as:

$$q_{noise} = \begin{cases} 1 & \text{if } K_{dp} \geq 0.5 \\ 2K_{dp} & \text{if } 0 < K_{dp} \leq 0.5 \\ 0 & \text{if } K_{dp} < 0 \end{cases} \quad (34)$$

Low values of $K_{dp}$ are referred to variation of $\Phi_{dp}$ comparable with the measurements phase noise (few degrees) and the $K_{dp}$ estimation become of poor quality. Figure 11 shows a graphic representation of eq. (34), where the index is considered unreliable for the $K_{dp}$ less than 0.5 degrees km$^{-1}$.

[Diagram showing the scheme of $q_{noise}$]
Figure 12 shows an example of the quality index associated to the $K_{dp}$, and referred to an event occurred on April 26, 2011 at 9:26 UTC. In the figure, on the left panel, is also shown the PPI of $K_{dp}$ at the lowest elevation, derived from $\Phi_{dp}$ with the IFD scheme.

![Figure 12](image)

Figure 12. PPI of $K_{dp}$ and the corresponding Noise Quality index polar map.

The high values of $K_{dp}$ refer to a convective event, which corresponds to a reliable value of $q_{\text{noise}}$ index.

ATTENUATION CORRECTION

The common polarimetric approach for compensating rain path attenuation is based on the assumed linearity, excellent in both C- and X-band, between specific attenuation ($A_H$) as well as differential attenuation ($A_{dp}$) and specific differential phase ($K_{dp}$) (Bringi et al. 2004):

$$A_H = \gamma_H K_{dp}$$  \hspace{1cm} (35)
$$A_{dp} = \alpha A_H^\beta$$  \hspace{1cm} (36)

It is known that the coefficients $\gamma_H$, $\alpha$ and $\beta$ are variable, depending on raindrop size, shape and temperature (Jameson, 1992).

The parameterization adopted in the present work was obtained from T-Matrix scattering simulations based on the drop size distribution (DSD) observations collected with a disdrometer. They are the same coefficients obtained during the field campaign in Fortaleza (Schneebeli et al., 2012), as shown in table 2 and here repeated: $\gamma_H = 0.212$, $\alpha = 0.117$ and $\beta = 1.265$.

Through the following relation (Bringi and Chandrasekar, 2001), valid for $Z_{bh}$ it is possible to derive the attenuation correction.

$$Z'_{h}(r) = Z_{h}(r) - 2 \int_{r_0}^{r_N} A_H(s) \, ds = Z_{h}(r) - 2 \cdot \text{PIA}(r_0, r_N)$$  \hspace{1cm} (37)

being $Z'_{h}$ the reflectivity attenuated by rain and PIA (dB) the single path integrated attenuation between $r_0$ and range $r_N$. Similar relationship is also obtainable for the $Z_{dr}$ using Eq. (36).
It is worth specifying that attenuation is estimated until the slant range $r_N$, that is the range gate corresponding to the altitude 500 m under the freezing layer height. At farther ranges, attenuation and differential attenuation accumulated until $r_N$ are applied to correct reflectivity and differential reflectivity, respectively. As previously mentioned the identification of the freezing level height is important for defining the application limit of the rain attenuation correction. The melting layer (ML) is characterized by an important attenuation effect at X-band and higher frequencies. Measurements at X-band by Bellon et al. (1997) showed that the attenuation effect of the ML could be 3–5 times larger than the one caused by the rain below. The $P_{HV}$ exhibits an important polarimetric signature of the melting layer and together with the reflectivity can be used for the identification of the freezing level (e.g., Matrosov et al. 2007, Wolfensberger et al. 2015). For the sake of completeness, it must be specified that wet hail attenuation has not been compensated for. Indeed, it can be very tricky and uncertain, depending on many factors, including particle size, shape, as well as the water coat thickness that can modify the particle shape and fall orientation (Rasmussen and Heymsfield, 1987).

Figure 13 shows the PPI of $Z_h$ at the lowest elevation ($1.8^\circ$), before and after the application of the path attenuation correction procedure and referred to an event occurred on April 26, 2011 at 9:26 UTC.

![Figure 13](image1.png)

**Figure. 13** $Z_h$ (left panel), $Z_h$ corrected for attenuation (right panel) and the relative correction factor (central panel) at the lowest elevation ($1.8^\circ$), for an event occurred on April 26, 2011 at 9:26 UTC.

Next figure 14 shows, for the same event, a radar imaging of a vertical cut (VCUT) of reflectivity (in dBZ up to 14 km) from Fortaleza radar to a distance of 100 km in south east direction (169 degrees), corresponding to the direction of maximum reflectivity.

![Figure 14](image2.png)

**Figure. 14** VCUT of $Z_h$ before (left panel) and after (right panel) the attenuation correction along the direction of the maximum value for an event occurred on April 26, 2011 at 9:26 UTC.
As a further example, figure 15 shows the range profiles of the reflectivity before (blue line) and after (red line) the application of the path attenuation correction for the same event observed, by the radar located in Fortaleza, on April 26, 2011 at 9:26 UTC. Two directions were taken into consideration: one corresponding to the maximum intensity of the signal (left) and the other containing the largest number of bins (right).

![Figure 15](image15.png)

**Figure 15** Range profile of $Z_h$ at 1.8° elevation respectively along 169° (left) and along 140° of azimuth (right), before (blue line) and after (red line) the path attenuation correction for the event occurred on April 26, 2011 at 9:26 UTC.

Usually, for dual-polarization systems there are a variety of possible solutions of attenuation correction, all based on the use of differential phase shift (Vulpiani et al., 2008), so it is recommended to evaluate the reflectivity corrected for quality as well. The quality index associated with rain path attenuation can be defined as

$$q_{att} = \begin{cases} 
1 & \text{for } PIA < PIA_{min} \\
0.5 & \text{for } PIA > PIA_{max} \\
\frac{2PIA_{max} - PIA_{min} - PIA}{2(PIA_{max} - PIA_{min})} & \text{for } PIA_{min} \leq PIA \leq PIA_{max}
\end{cases}$$  \hspace{1cm} (38)

where $PIA_{min} = 3$ dB and $PIA_{max} = 15$ dB;

In presence of events with fast and wide differential phase fluctuation and consequently high signal correction ($PIA > 15$ dB) the quality index is considered less reliable and reduced up to 50% (0.5). Figure 16 shows a graphic representation of eq. (38).

![Figure 16](image16.png)

**Figure 16.** Scheme of $q_{att}$

Examples of the attenuation quality index map are shown in Figure 17. They are referred to convective events occurred respectively in Fortaleza on April 26, 2011 at 9:26 UTC (left), in São José dos Campos on November 13, 2011 at 22:06 UTC (center) and in Manaus on February 21, 2014 at 8:50 UTC (right).
Figure 17. Polar map of the Attenuation Quality index at lower elevation angle associated to radar located in Fortaleza on April 26, 2011 at 9:26 UTC (left), in Sao José dos Campos on November 13, 2011 at 22:06 UTC (center) and in Manaus on February 21, 2014 at 8:50 UTC (right).

OVERALL QUALITY

After the attenuation is evaluated and, eventually, compensated, the final radar data quality $Q$ can be retrieved by combining all the considered quality indicators. All the partial quality matrices are used in a multiplicative combination:

$$Q = q_{\text{blank}} \cdot q_{\text{range}} \cdot \max(q_{\text{loss}}, q_{\text{noise}})$$ (39)

where $q_{\text{range}}$, defined as

$$q_{\text{range}} = q_{\text{distance}} \cdot q_{\text{VPR}}$$ (40)

is obtained by combining the quality indexes that essentially are related to the geometric characteristics (distance, elevation) and defined respectively in Eqs. (29) and (30). The index $q_{\text{loss}}$, instead, defined as

$$q_{\text{loss}} = q_{\text{PBB}} \cdot q_{\text{att}}$$ (41)

is obtained by grouping the quality indices relating to the signal ($Z_h$) correction, using indices defined respectively in Eqs. (28) and (38). The index $q_{\text{noise}}$, defined in Eq. (34), is also related to the signal ($K_{dp}$). Of the latter two is considered the one with the highest value.

If a sector of radar observation is empty (no data) due to clutter or radar inhibition to transmit, the overall quality of the data is compromised in that area. Using occurrence maps (Fig. 18), it is possible to locate blank areas and apply the $q_{\text{blank}}$ index: it is always 1 except in the empty sector where it is zero.

The quality associated with the rain rate products at time $t$ ($Q(R_t)$) is the same as for the radar data (errors associated with the inversion process are not considered).

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RAINFALL ESTIMATION

The quantitative estimation of rain rates using meteorological radar has been one of main themes in radar meteorology and radar hydrology. The simplest rainfall algorithm is the Z–R relation. We know that once a reflectivity value is obtained as correctly as possible, it can be converted into rainfall by means of a power-law type relationship:

$$ R(Z_h) = aZ_h^b $$

(42)

where $R$ is rainfall rate in mm h$^{-1}$ units and $Z_h$ in mm$^3$m$^{-3}$, while $a$ and $b$ are two coefficients whose value depends on the type of precipitation. The problem of determining coefficients is one of the most discussed in radar meteorology; in literature, there are many pairs of coefficients calculated for different types of precipitation and tested experimentally by comparison with a network of precipitation sensors located in the radar-swept area. It is clear, however, that this relationship is purely empirical and subject to dependency uncertainties mainly by the distribution of the drop size (DSD) in the volume under consideration and the time duration of the measurement.
The use of polarimetric quantities clearly provides better results in terms of precipitation estimation, being able to employ more than the reflectivity \( Z_h \) also the specific phase \( K_{dp} \) and the differential reflectivity \( Z_{dr} \) in various combinations. The most common estimation models can be distinguished in three main categories:

i) \( R = R(Z_h, Z_{dr}) \)

ii) \( R = R(K_{dp}) \)

iii) \( R = R(Z_{dr}, K_{dp}) \)

where each one has advantages and disadvantages, and where each error in the polarimetric measurement translate into the structure of algorithms involving \( Z_h, Z_{dr} \) and \( K_{dp} \).

For the precipitation estimation, it was decided to adopt the R-Z and the R-\( K_{dp} \) relations. Indeed, the algorithms to estimate rainfall from \( K_{dp} \) are particularly attractive at wavelengths such as X-band: \( K_{dp} \) being derived from phase measurements, it is unaffected by absolute calibration error and attenuation caused by precipitation along the propagation path (Bringi and Chandrasekar, 2001). The R-\( K_{dp} \) relationship can be written as:

\[
R(K_{dp}) = c \cdot (|K_{dp}|)^d \cdot \text{sign}(K_{dp})
\]  

(43)

with \( K_{dp} \) in deg/km.

For the parameterization of \( R(Z_h) \) and \( R(K_{dp}) \) (Eqs. 42 and 43) were used respectively, coefficients of Marshall and Palmer, 1948 (MP48) and those of the study carried out during the campaign in Fortaleza by Schneebeli et al., 2012 (SC12) (Eq. 16). Another pair of coefficients is adopted for R-\( K_{dp} \) model, using Bringi and Chandrasekar, 2001 (BC01). Figure 18 shows the trend of the estimators with different pairs of coefficients.

**Figure. 18** Rain rate estimation using \( R(Z_h) \) model (top) and \( R(K_{dp}) \) model (bottom) for different coefficients: Marshall and Palmer, 1948 (MP48), Schneebeli et al., 2012 (SC12) and Bringi and Chandrasekar, 2001 (BC01).

The \( R(Z_h) \) and \( R(K_{dp}) \) parameterization is summarized in the following table.

<table>
<thead>
<tr>
<th></th>
<th>( R(Z_h) )</th>
<th></th>
<th>( R(K_{dp}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( a )</td>
<td>( b )</td>
<td>( c )</td>
</tr>
<tr>
<td>MP48</td>
<td>0.0208</td>
<td>0.680</td>
<td>15.813</td>
</tr>
<tr>
<td>SC12</td>
<td>0.0098</td>
<td>0.680</td>
<td>19.193</td>
</tr>
</tbody>
</table>

**Table 5.** Parameters of \( R(Z_h) \) and \( R(K_{dp}) \) power law relations in X-band
The employ of radar reflectivity for estimating precipitation is frequently subject to underestimation (Rinollo et al. 2015), especially when is used the lowest beam map (LBM). In order to reduce this effect an additional polarimetric rainfall algorithm, proposed by Vulpiani et al. (2015), based on the use of reflectivity factor and specific differential phase, is applied. With the aim of gradually using Kdp at increasing rainfall intensities, the combined algorithm takes the form of a weighted sum

\[ R_q = q_{\text{Noise}} \cdot R_K + (1 - q_{\text{Noise}}) \cdot R_Z \]  

(44)

where \( R_Z \) and \( R_K \) are the rainfall estimates obtained by applying specific power laws (Eqs. 42 and 43) to the lowest non-shielded radar bin of \( Z_H \) and Kdp, respectively. The coefficients adopted to derive \( R_K \) and \( R_Z \) are shown in table 5, while the weight is the quality index \( q_{\text{noise}} \), defined in Eq. (34).

It also introduces a combined polarimetric rainfall algorithm with another type of weighing, which averages more between the contributions of \( Z_H \) and Kdp.

\[ R_q = \frac{q_{\text{loss}} \cdot R_Z + q_{\text{Noise}} \cdot R_K}{q_{\text{loss}} + q_{\text{Noise}}} \]  

(45)

where \( R_K \) and \( R_Z \) parameters are the same of Eq. (44), while the weights are the quality indices \( q_{\text{loss}} \) and \( q_{\text{noise}} \) defined in Eqs. (41) and (34).

The different estimators, used with the various coefficient combinations, are summarized as follows:

1) \( R_Z \) : Eq. 42 with MP48 coefficients.
2) \( R_{K1} \) : Eq. 43 with SC12 coefficients.
3) \( R_{K2} \) : Eq. 43 with BC01 coefficients.
4) \( R_{q1} \) : Eq. 45 with MP48 and SC12 coefficients.
5) \( R_{q2} \) : Eq. 45 with MP48 and BC01 coefficients.
6) \( R_{q1V15} \) : Eq. 44 with MP48 and SC12 coefficients.
7) \( R_{q2V15} \) : Eq. 44 with MP48 and BC01 coefficients.

Below, Figures 19-20, show an example of rainfall estimation. It refers to an event occurred, during the Fortaleza campaign, on April 26, 2011 at 9:26 in which all the estimators (\( R(Z_H) \), \( R(K_{dp}) \) and \( R(Z_H, K_{dp}) \)) applied are depicted.

**Figure. 19** Rain rate estimation using \( R_Z \) model (left), \( R_{K1} \) model (centre) and \( R_{K2} \) model (right) for an event occurred on April 26, 2011 at 9:26 UTC.
Figure. 20 Rain rate estimation using $R_{q1}$ model (top left), $R_{q2}$ model (top right), $R_{q1V=15}$ model (bottom left) and $R_{q2V=15}$ model (bottom right) for an event occurred on April 26, 2011 at 9:26 UTC.

All the QPE radar maps are generated using the lowest beam map as compromise between minimizing beam height over the ground and minimizing partial beam blocking and ground clutter effects. Rainfall intensity, based on the $R_Z$ model (Fig. 19 left), is on average less than the estimates of other models, especially during convective events. The latter are highlighted by the models that use $K_{dp}$ alone or in combination.

7. ASSESSMENT OF PROCESSING METHODOLOGY

The methodology of processing has been the subject of an evaluation by comparing the precipitation estimates with the measurements of rain gauges installed, during the CHUVA campaign, near Manaus, in the north of Brazil and in the Vale do Paraíba, in the south of Brazil.

During the Manaus campaign, the X-band polarimetric radar was installed in the Amazon rainforest about 60 km from Manaus between the Rio Negro and the Amazon rivers (Lat. 3° 12’ 46.86’’ S, Lon. 60° 35’ 53.92’’ W, 69 m ASL). The X-Band radar scanning strategy has produced one volume scan with 15 elevations (varying from 0.5 to 30 degrees). Two measurement sites (called T3 and Manacapuru) were established and equipped with rain-gauges. T3 is located in the same position of the radar site while Manacapuru is approximately 10 km from the radar site (Fig. 21).
During the Vale do Paraíba campaign, the X-band polarimetric radar was installed near São José dos Campos (Lat. 23° 12’ 31.33” S, Lon. 45° 57’ 7.87” W, 650 m ASL) above the roof of UNIVAP (Vale do Paraíba University) in São Paulo State in an elevated valley between the Mantiqueira and Serra do Mar mountain ranges. The X-Band radar scanning strategy has produced a volume scan with 13 elevations (varying from 1 to 25 degrees) which are contained within a range of 6 minutes, or 10 scans per hour. Seven measurement sites (called UNIVAP, CTA, IEAV, JAMBEIRO, CESP, POUSADA and CARAGUA) were established and equipped with rain-gauges. UNIVAP is located in the same position of the radar site while the others are located respectively 9, 11, 22, 43, 51 and 75 km from the radar site, approximately along the same direction (Fig. 22).

Data collected during these two campaigns have been used in the evaluation. Specifically, in the Manaus campaign, the case studies analyzed are 8 days between February and March 2014 (15, 21, 23, 24, 25 26 February and 2, 8 March) while in the Vale do Paraíba campaign 6 days were analyzed between November and December 2011 (11, 13 November and 1, 8, 14, 20 December). The first step is to identify cases with remarkable precipitation and the time overlap between radar observations and the rain-gauges measurements.
The radar-raingauges comparison was made by first converting the values of the two instruments into comparable units. Rain-gauge data acquisitions are performed with a temporal interval of 1 minute (it’s an accumulated expressed in mm), and converted into hourly accumulated summing the acquisitions of an hour. The radar scan periodicity was 6 minutes, so to match this data with gauge data an hourly value is computed by means the arithmetic mean of the rainfall intensities within the given hour. The hourly values are then summed to obtain the precipitation accumulated and hereafter called SRT (Surface Rainfall Total accumulated).

In order to perform the inter-comparisons among radar estimates and gauges measurements, it is necessary to match the position of the rain-gauge with the corresponding radar cell.

Since with distance from the radar changes the cell size (tends to increase in azimuth) and also changes the height between the rain gauge and the radar beam, it is not said that the measurement acquired by the rain-gauge corresponds to the above cell. Furthermore, the fact that radar retrieval is an areal measurement whereas the rain-gauge is a point measurement introduces an extra degree of uncertainty. So, the polar radar map is converted into a regular cartesian; the position of the rain-gauge is detected in the new coordinates and around it a grid is selected (red square in figure 23) with a resolution of 200 m.

Since the variability of precipitation fields strongly depends on the way radar rain-gauge spatial coupling are considered, a meaningful comparison is not trivial. For this reason, different spatial coupling modes are used:

1) **Nv** (Nearest Value). The value inside the grid closest to the rain gauge value.
2) **Mean**. The average value between the grid internal values.
3) **Max** (Maximum). The maximum between the values in the grid.
4) **Median**. The value separating the higher half of the grid internal values, from the lower half.

The quality of the comparison is evaluated using the following indicators. The absolute error (ERR) is defined as the difference between the hourly precipitation estimates from radar (R) with the measured data from rain-gauges indicated instead with G:

\[
\text{ERR} = R - G
\]

pointing with angle brackets the average with respect to time, we introduce the following:

Mean error or **BIAS** (optimum value 0):

\[
\text{BIAS} = \langle \text{ERR} \rangle
\]

Absolute Mean Error (**MAE**):

\[
\text{MAE} = \langle |\text{ERR}| \rangle
\]
Root Mean Square Error (**RMSE**):

\[ RMSE = \sqrt{\langle (ERR)^2 \rangle} \]  

(49)

Fractional Standard Error (**FSE**):

\[ FSE = \sqrt{\frac{\langle (ERR)^2 \rangle}{\langle G \rangle}} \]  

(50)

Coefficient of correlation (**Corr**):

\[ Corr = \frac{\sigma_{R,G}}{\sigma_R \cdot \sigma_G} \]  

(51)

where \( \sigma_{R,G} \), \( \sigma_R \) and \( \sigma_G \) indicate, respectively, the covariance of the radar observations and rain-gauges, the standard deviation of the radar observations and the standard deviation of the rain-gauge observations, defined as:

\[ \sigma_{R,G} = \langle (R - \langle R \rangle) \times (G - \langle G \rangle) \rangle \quad \sigma_R = \sqrt{\langle (R - \langle R \rangle)^2 \rangle} \quad \sigma_G = \sqrt{\langle (G - \langle G \rangle)^2 \rangle} \]  

(52)

Mean-Field Ratio Bias (**MRB**):

\[ MRB = \frac{\langle G \rangle}{\langle R \rangle} \]  

(53)

Below are some examples of case studies used in this analysis from the measurement campaigns of Manaus and Vale do Paraiba.

**MANAUS CAMPAIGN: FEBRUARY 21, 2014**

The following figures (24-26) show the SRT 24 hourly accumulated obtained by the different rainfall estimators employed and refers to 24 hours of February 21, 2014 from 00:00 to 24:00 UTC. The numeric values shown in the maps correspond to the 24-hour cumulative values detected by the rain gauges.

![Figure 24](https://example.com/figure24.png)

**Figure 24.** SRT 24 hourly accumulated using \( R_2 \) model (left), \( R_{K1} \) model (centre) and \( R_{K2} \) model (right) for the event occurred on 2014, February 15. The corresponding values accumulated by the rain gauges are shown in the map.
Figure 25. SRT 24 hourly accumulated using $R_{q1}$ model (left), $R_{q2}$ model (right), for the event occurred on 2014, February 21. The corresponding values accumulated by the rain gauges are shown in the map.

Figure 26. SRT 24 hourly accumulated using $R_{q1Vu15}$ model (left) and $R_{q2Vu15}$ model (right), for the event occurred on 2014, February 21. The corresponding values accumulated by the rain gauges are shown in the map.

During the day, convective rain events took place as can be seen from the SRT map and the accumulated value detected by the rain gauges. Compared with 24-h gauge measurements, radar QPE based on $R_z$ estimator (Fig. 24, left), shows an underestimation. The behavior of $K_{dp}$-based estimators, on the other hand, seems to follow as measured by the rain-gauges, especially for those closest to the radar site. Considering shorter accumulation periods (1 hour), the rainfall algorithms estimates are compared with rain gauges acquisitions. The following figure shows the 1-hour cumulative sum of the radar estimates compared with the rain gauges cumulations (red curve) and referred to the 24 hours of February 21 for different types of radar- raingauge coupling.
Figure 27. Time series of 1-hour precipitation cumulative sum at Manacapuru for the event occurred on 2014, February 21. Different radar-raingauge coupling are shown: Nv (top left), Mean (top right), Max (bottom left) and Median (bottom right).

As shown in the previous time series (Fig. 27) and in the SRT maps (Figs. 24-26), at the Manacapuru site there is a general underestimation of radar rainfall estimations based solely on the reflectivity. The high values of the cumulative sum using the maximum (Fig. 27, bottom left panel) are certainly related to the type of radar-gauges coupling. R$_Z$ models, alone and combined appear to have an excellent behavior by tracking the accumulated rainfall profile provided by the rain gauge. The most performing radar-gauge coupling mode is certainly the Nv also confirmed by the error indices scores (Table 6).

<table>
<thead>
<tr>
<th>Nv</th>
<th>Mean</th>
<th>R$_Z$</th>
<th>R$_{Q1}$</th>
<th>R$_{Q2}$</th>
<th>R$_{Q1V15}$</th>
<th>R$_{Q2V15}$</th>
<th>R$_{Q1V15}$</th>
<th>R$_{Q2V15}$</th>
<th>R$_{Q1V15}$</th>
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</thead>
<tbody>
<tr>
<td>Corr</td>
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<td>0.995</td>
<td>0.997</td>
<td>0.998</td>
<td>0.997</td>
<td>0.994</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bias</td>
<td>-3.19</td>
<td>-0.61</td>
<td>0.18</td>
<td>-2.04</td>
<td>-1.59</td>
<td>-1.09</td>
<td>-0.20</td>
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<td></td>
</tr>
<tr>
<td>MAE</td>
<td>3.19</td>
<td>0.91</td>
<td>0.59</td>
<td>2.06</td>
<td>1.59</td>
<td>1.11</td>
<td>0.75</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>RMSE</td>
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<td>1.40</td>
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<td>3.39</td>
<td>2.43</td>
<td>1.63</td>
<td>0.99</td>
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<td>FSE</td>
<td>3.43</td>
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<td>1.03</td>
<td>0.63</td>
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</table>

<table>
<thead>
<tr>
<th>Nv</th>
<th>Mean</th>
<th>R$_Z$</th>
<th>R$_{Q1}$</th>
<th>R$_{Q2}$</th>
<th>R$_{Q1V15}$</th>
<th>R$_{Q2V15}$</th>
<th>R$_{Q1V15}$</th>
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<th>R$_{Q1V15}$</th>
<th>R$_{Q2V15}$</th>
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<tbody>
<tr>
<td>Corr</td>
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<td>0.995</td>
<td>0.996</td>
<td>0.998</td>
<td>0.998</td>
<td>0.993</td>
<td>0.998</td>
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<td></td>
</tr>
<tr>
<td>Bias</td>
<td>-3.73</td>
<td>-0.67</td>
<td>0.10</td>
<td>-2.09</td>
<td>-1.63</td>
<td>-1.14</td>
<td>-0.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAE</td>
<td>3.73</td>
<td>0.90</td>
<td>0.75</td>
<td>2.09</td>
<td>1.64</td>
<td>1.14</td>
<td>1.01</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>RMSE</td>
<td>6.10</td>
<td>1.23</td>
<td>1.06</td>
<td>3.31</td>
<td>2.34</td>
<td>1.48</td>
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<td></td>
<td></td>
</tr>
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<td>FSE</td>
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<td>1.49</td>
<td>0.94</td>
<td>0.73</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table 6: Overall error scores computed for hourly cumulated rainfall at Manacapuru site. Four radar-raingauges spatial coupling modes are used: Nearest value, Mean, Max and Median.
MANAUS CAMPAIGN: FEBRUARY 26, 2014

The following figures (28-30) show the SRT 24 hourly accumulated obtained by the different rainfall estimators employed and refers to 24 hours of February 26, 2014 from 00:00 to 24:00 UTC. The numeric values shown in the maps correspond to the 24-hour cumulative values detected by the rain gauges.

Figure 28. SRT 24 hourly accumulated using Rz model (left), Rk1 model (centre) and Rk2 model (right) for the event occurred on 2014, February 26. The corresponding values accumulated by the rain gauges are shown in the map.

Figure 29. SRT 24 hourly accumulated using Rq1 model (left), Rq2 model (right), for the event occurred on 2014, February 26. The corresponding values accumulated by the rain gauges are shown in the map.

Figure 30. SRT 24 hourly accumulated using Rq1Vu15 model (left) and Rq2Vu15 model (right), for the event occurred on 2014, February 26. The corresponding values accumulated by the rain gauges are shown in the map.
This day is characterized by stratiform precipitation in the morning, mid-afternoon convective precipitation and subsequent extensive stratiform precipitation coverage. Compared with 24-h gauge measurements, radar QPE based on $R_z$ estimator continues to underestimate while $K_{dp}$-based algorithms seem have a good behavior especially when combined with reflectivity ($R_q$ models).

The comparison of hourly accumulated between radar estimates and rain gauge is shown in the cumulative sum of figure 31.

In the Nv radar-gauge coupling mode, all the estimators present a good behavior by tracking the accumulated rainfall profile provided by the rain gauge especially with the light rain, while overestimated slightly with the most intense precipitation. As for the other coupling modes all overestimates except the Mean and Median where the algorithm based solely on reflectivity underestimates.

![Figure 31. Time series of 1-hour precipitation cumulative sum at Manacapuru for the event occurred on 2014, February 26. Different radar-raingauge coupling are shown: Nv (top left), Mean (top right), Max (bottom left) and Median (bottom right).](image)

The indication of the goodness of the radar estimate compared to the expected value (raingauge data) can be deduced from the error indices shown in table 7.
Table 7: Overall error scores computed for hourly cumulated rainfall at Manacapuru site. Four radar-raingauges spatial coupling modes are used: Nearest value, Mean, Max and Median.

MANAUS CAMPAIGN: MARCH 8, 2014

The following figures (32-34) show the SRT 24 hourly accumulated obtained by the different rainfall estimators employed and refers to 24 hours of March 18, 2011 from 00:00 to 24:00 UTC. The numeric values shown in the maps correspond to the 24-hour cumulative values detected by the rain gauges.

![Figure 32](image1.png)  ![Figure 33](image2.png)

Figure 32. SRT 24 hourly accumulated using Rz model (left), Rk1 model (centre) and Rk2 model (right) for the event occurred on 2014, March 8. The corresponding values accumulated by the rain gauges are shown in the map.

Figure 33. SRT 24 hourly accumulated using Rq1 model (left), Rq2 model (right), for the event occurred on 2014, March 8. The corresponding values accumulated by the rain gauges are shown in the map.
Figure 34. SRT 24 hourly accumulated using $R_{q1Vu15}$ model (left) and $R_{q2Vu15}$ model (right), for the event occurred on 2014, March 8. The corresponding values accumulated by the rain gauges are shown in the map.

On this date we have extensive and intense stratiform precipitation on Manaus (accumulated 100mm/24h). The hourly cumulation of the radar precipitation estimates in the 24 hours for the different types of radar-raingage coupling are employed and compared with the rain-gauge accumulations (red curve).

Figure (35) confirm the good performance of $K_p$-based algorithms, alone and combined, and especially in the radar-raingage coupling Nv. Even the error index scores (Table 8) show, for this matching, the goodness of the estimation.

Figure 35. Time series of 1-hour precipitation cumulative sum at Manacapuru for the event occurred on 2014, March 8. Nv (top left), Mean (top right), Max (bottom left) and Median (bottom right) indicate the radar-raingage coupling modes.

Performance indicators for different types of estimators are shown in the following table.
Table 8 Overall error scores computed for hourly cumulated rainfall at Manacapuru site. Four radar-raingauges spatial coupling modes are used: Nearest value, Mean, Max and Median.

Vale do Paraiba campaign: November 13, 2011

The following figures (36-38) show the SRT 24 hourly accumulated obtained by the different rainfall estimators employed and refers to 24 hours of November 13, 2011 from 00:00 to 24:00 UTC during the Vale do Paraiba campaign. This date is characterized by extensive convection and stratiform area. The numeric values shown in the maps correspond to the 24-hour cumulative values detected by the rain gauges.

Figure 36. SRT 24 hourly accumulated using \(R_z\) model (left), \(R_{K1}\) model (centre) and \(R_{K2}\) model (right) for the event occurred on 2011, November 13. The corresponding values accumulated by the rain gauges are shown in the map.
Figure 37. SRT 24 hourly accumulated using $R_{q1}$ model (left), $R_{q2}$ model (right), for the event occurred on 2011, November 13. The corresponding values accumulated by the rain gauges are shown in the map.

Figure 38. SRT 24 hourly accumulated using $R_{q1Vu15}$ model (left) and $R_{q2Vu15}$ model (right), for the event occurred on 2011, November 13. The corresponding values accumulated by the rain gauges are shown in the map.

During the day both convective and stratiform rain events occurred as can be seen from the SRT maps and accumulated values detected by the rain gauges. Compared with 24-h gauge measurements, radar QPE based on $R_z$ estimator (Fig. 36, left), shows an underestimation especially with convective events. The behavior of $K_{dp}$-based estimators, on the other hand, seems to follow as measured by the rain-gauges.

The rainfall algorithms estimates are compared with the raingauges acquisitions and an example of the results is shown in the following figures (Figs. 39, 40). They represent the 1-hour cumulative sum of the radar estimates compared with the raingauges accumulated (red curve) and refer to two measurement sites: Jambeiro and the Institute of Advanced Studies from the Department of Aerospace Science and Technology (IEAV) for the 24 hours of November 13 and for different types of radar-raingauge coupling.
Figure 39. Time series of 1-hour precipitation cumulative sum at Jambeiro for the event occurred on 2011, November 13. Different radar-raingauge coupling are shown: Nv (top left), Mean (top right), Max (bottom left) and Median (bottom right).

The most performing radar-gauge coupling mode is certainly the Nv (Nearest value) also confirmed by the scores of error indices (Table 9). Moreover, Max tends to overestimate while Mean and Median, with similar behavior, tend to underestimate.

<table>
<thead>
<tr>
<th>Nv</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_z )</td>
<td>( R_{K1} )</td>
</tr>
<tr>
<td>Corr</td>
<td>0.99</td>
</tr>
<tr>
<td>Bias</td>
<td>-0.76</td>
</tr>
<tr>
<td>MAE</td>
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</tr>
<tr>
<td>RMSE</td>
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</tr>
<tr>
<td>FSE</td>
<td>0.82</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Max</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_z )</td>
<td>( R_{K1} )</td>
</tr>
<tr>
<td>Corr</td>
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</tr>
<tr>
<td>Bias</td>
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</tr>
<tr>
<td>MAE</td>
<td>6.77</td>
</tr>
<tr>
<td>RMSE</td>
<td>3.93</td>
</tr>
<tr>
<td>FSE</td>
<td>3.78</td>
</tr>
</tbody>
</table>

Table 9: Overall error scores computed for hourly cumulated rainfall at Jambeiro site. Four radar-raingauges spatial coupling modes are used: Nearest value, Mean, Max and Median.
Figure 40. Time series of 1-hour precipitation cumulative sum at IEAV for the event occurred on 2011, November 13. Different radar-raingauge coupling are shown: Nv (top left), Mean (top right), Max (bottom left) and Median (bottom right).

In the Nv (Nearest value) radar-raingauge coupling mode, all the estimators present an excellent behavior by tracking the accumulated rainfall profile provided by the rain gauge. This is confirmed by the 1-hour cumulative sum (Fig. 40 top left) and by the scores of error indices (Table 10). In other data coupling modes all algorithms have an overestimation.

<table>
<thead>
<tr>
<th>Nv</th>
<th>Rz</th>
<th>Rk1</th>
<th>Rk2</th>
<th>Rq1</th>
<th>Rq2</th>
<th>Rq1Vu15</th>
<th>Rq2Vu15</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
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<td>0.06</td>
<td>0.10</td>
<td>0.20</td>
<td>0.01</td>
</tr>
<tr>
<td>MAE</td>
<td>0.29</td>
<td>0.35</td>
<td>0.48</td>
<td>0.08</td>
<td>0.10</td>
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<tr>
<td>RMSE</td>
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<td>0.14</td>
<td>0.19</td>
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<tr>
<td>FSE</td>
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<td>0.69</td>
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<td>0.20</td>
<td>0.46</td>
<td>0.02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean</th>
<th>Rz</th>
<th>Rk1</th>
<th>Rk2</th>
<th>Rq1</th>
<th>Rq2</th>
<th>Rq1Vu15</th>
<th>Rq2Vu15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corr</td>
<td>0.93</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
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</tr>
<tr>
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<td>1.08</td>
<td>1.96</td>
<td>3.75</td>
<td>5.26</td>
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<tr>
<td>MAE</td>
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<td>5.96</td>
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<td>1.98</td>
<td>3.75</td>
<td>5.26</td>
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<tr>
<td>RMSE</td>
<td>3.29</td>
<td>4.49</td>
<td>5.82</td>
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<td>2.31</td>
<td>3.84</td>
<td>5.26</td>
</tr>
<tr>
<td>FSE</td>
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<td>6.14</td>
<td>6.26</td>
<td>2.83</td>
<td>2.56</td>
<td>5.27</td>
<td>3.34</td>
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<table>
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<tr>
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<th>Rz</th>
<th>Rk1</th>
<th>Rk2</th>
<th>Rq1</th>
<th>Rq2</th>
<th>Rq1Vu15</th>
<th>Rq2Vu15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corr</td>
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<td>0.98</td>
<td>0.99</td>
<td>0.58</td>
<td>0.66</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>Bias</td>
<td>5.79</td>
<td>8.83</td>
<td>9.73</td>
<td>7.72</td>
<td>9.47</td>
<td>9.81</td>
<td>8.93</td>
</tr>
<tr>
<td>MAE</td>
<td>5.80</td>
<td>8.83</td>
<td>9.73</td>
<td>7.73</td>
<td>9.47</td>
<td>9.94</td>
<td>9.34</td>
</tr>
<tr>
<td>RMSE</td>
<td>8.06</td>
<td>8.76</td>
<td>9.32</td>
<td>8.42</td>
<td>9.41</td>
<td>9.72</td>
<td>4.28</td>
</tr>
<tr>
<td>FSE</td>
<td>9.78</td>
<td>8.56</td>
<td>9.43</td>
<td>3.95</td>
<td>9.85</td>
<td>10.55</td>
<td>3.18</td>
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<th>Rz</th>
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<th>Rk2</th>
<th>Rq1</th>
<th>Rq2</th>
<th>Rq1Vu15</th>
<th>Rq2Vu15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corr</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Bias</td>
<td>-2.41</td>
<td>2.97</td>
<td>5.80</td>
<td>0.76</td>
<td>1.49</td>
<td>3.65</td>
<td>-4.08</td>
</tr>
<tr>
<td>MAE</td>
<td>2.51</td>
<td>3.64</td>
<td>5.80</td>
<td>1.89</td>
<td>1.96</td>
<td>3.65</td>
<td>4.12</td>
</tr>
<tr>
<td>RMSE</td>
<td>3.64</td>
<td>6.37</td>
<td>4.81</td>
<td>2.09</td>
<td>2.15</td>
<td>3.74</td>
<td>4.06</td>
</tr>
<tr>
<td>FSE</td>
<td>4.98</td>
<td>6.08</td>
<td>7.96</td>
<td>2.81</td>
<td>2.94</td>
<td>3.13</td>
<td>2.93</td>
</tr>
</tbody>
</table>

Table 10: Overall error scores computed for hourly cumulated rainfall at IEAV site. Four radar-raingauges spatial coupling modes are used: Nearest value, Mean, Max and Median.
VALE DO PARAIBA CAMPAIGN: DECEMBER 14, 2011

The following figures (41-43) show the SRT 24 hourly accumulated obtained by the different rainfall estimators employed and refers to 24 hours of December 14, 2011 from 00:00 to 24:00 UTC. This date is characterized by severe convective events that affected the valley. The numeric values shown in the maps correspond to the 24-hour cumulative values detected by the rain gauges.

Figure 41. SRT 24 hourly accumulated using $R_z$ model (left), $R_{K1}$ model (centre) and $R_{K2}$ model (right) for the event occurred on 2011, December 14. The corresponding values accumulated by the rain gauges are shown in the map.

Figure 42. SRT 24 hourly accumulated using $R_{q1}$ model (left), $R_{q2}$ model (right), for the event occurred on 2011, December 14. The corresponding values accumulated by the rain gauges are shown in the map.

Figure 43. SRT 24 hourly accumulated using $R_{q1Vu15}$ model (left) and $R_{q2Vu15}$ model (right), for the event occurred on 2011, December 14. The corresponding values accumulated by the rain gauges are shown in the map.
Even in this case the $R_Z$ estimator continues to underestimate and not highlighting some maximum precipitation peaks. $K_{dp}$-based algorithms seems have a good behavior especially in the presence of convective events.

The comparison of hourly accumulated between radar estimates and rain gauge is shown in the cumulative sum of figure 44. Using the Nv radar-gauge coupling mode, all estimators have a slight underestimation but they still follow the accumulated rainfall profile provided by the rain gauge, both with light rain and with the most intense rainfall. As for the other coupling modes, they all underestimate except for the Max where, especially with light rain, overestimated.

Figure 44. Time series of 1-hour precipitation cumulative sum at CESP site for the event occurred on 2011, December 14. Different radar-rain gauge coupling are shown: Nv (top left), Mean (top right), Max (bottom left) and Median (bottom right).

The indication of the goodness of the radar estimate compared to the expected value (raingauge data) can be deduced from the error indices shown in table 11.
Overall Analysys

After comparing the radar estimates on individual rain-gauges for some case studies, the dataset, focuses on daily (24h) accumulations, was considered entirely. The rainy events analyzed has been collected during the Vale do Paraiba and Manaus campaigns, respectively between November and December 2011 and between February and March 2014.

The most performing radar-gauge coupling mode is the Nearest value, also confirmed by the error indices of the previous tables (6-11). Hereafter, only this spatial alignment mode will be considered.

A further indication of the deviation of radar estimates from the expected value (rain-gauges) can be deduced from the following scatter plots, showing the hourly accumulation of the estimators on the entire dataset, colored according to the density of the points and represented on a logarithmic scale to show their distribution at both low and high precipitation levels. In addition, a threshold (0.2 mm) was set to discriminate the accumulated above the minimum amount detectable by the rain gauges.

![Figure 45](image)

**Figure 45.** Scatter plot of RZ-gauges (left), of RKL-gauges (centre) and of RKE-gauges (right) hourly cumulated for the events occurred during the Vale do Paraiba campaign between November and December 2011.
Kdp-based algorithms seems have a good correlation, and in addition at medium-high rainfall accumulations \( R_{K2} \) and \( R_{q2Vu15} \) models are more accurate than other estimators. The latter are closely related and therefore have similar error scores (Table 12).

![Scatter plot](image1)

**Figure 46.** Scatter plot of \( R_{q1} \)-gauges (left) and of \( R_{q2} \)-gauges (right), hourly cumulated for the events occurred during the Vale do Paraiba campaign between November and December 2011.

![Scatter plot](image2)

**Figure 47.** Scatter plot of \( R_{q1Vu15} \)-gauges (left) and of \( R_{q2Vu15} \)-gauges (right) hourly cumulated for the events occurred during the Vale do Paraiba campaign between November and December 2011.

<table>
<thead>
<tr>
<th>Nv</th>
<th>( R_2 )</th>
<th>( R_{q1} )</th>
<th>( R_{q2} )</th>
<th>( R_{q1Vu15} )</th>
<th>( R_{q2Vu15} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corr</td>
<td>0.93</td>
<td>0.93</td>
<td>0.96</td>
<td>0.93</td>
<td>0.95</td>
</tr>
<tr>
<td>Bias</td>
<td>-0.71</td>
<td>-0.62</td>
<td>-0.34</td>
<td>-0.70</td>
<td>-0.52</td>
</tr>
<tr>
<td>MAE</td>
<td>0.75</td>
<td>0.75</td>
<td>0.50</td>
<td>0.80</td>
<td>0.65</td>
</tr>
<tr>
<td>RMSE</td>
<td>2.36</td>
<td>2.75</td>
<td>1.86</td>
<td>2.80</td>
<td>2.37</td>
</tr>
<tr>
<td>FSE</td>
<td>0.72</td>
<td>0.84</td>
<td>0.57</td>
<td>0.86</td>
<td>0.73</td>
</tr>
</tbody>
</table>

**Table 12** Overall error scores computed for hourly cumulated rainfall and for the Nearest value radar-raingauges spatial coupling.

Similar performance is also found in the Manaus data set where, due to a smaller number of points, this is most evident.
Figure 48. Scatter plot of $R_Z$-gauges (left), of $R_K1$-gauges (centre) and of $R_K2$-gauges (right) hourly cumulated for the events occurred during the Manaus campaign between February and March 2014.

Figure 49. Scatter plot of $R_{q1}$-gauges (left) and of $R_{q2}$-gauges (right) hourly cumulated for the events occurred during the Manaus campaign between February and March 2014.

Figure 50. Scatter plot of $R_{q1} Vu_{15}$-gauges (left) and of $R_{q2} Vu_{15}$-gauges (right) hourly cumulated for the events occurred during the Manaus campaign between February and March 2014.

The following error indices score (Table 13) confirms what seen previously in the Vale do Paraíba data set.
<table>
<thead>
<tr>
<th>Nv</th>
<th>R2</th>
<th>Rk1</th>
<th>Rk2</th>
<th>Rq1</th>
<th>Rq2</th>
<th>Rq2Vu15</th>
<th>Rq2Vu15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corr</td>
<td>0.79</td>
<td>0.96</td>
<td>0.97</td>
<td>0.89</td>
<td>0.92</td>
<td>0.96</td>
<td>0.98</td>
</tr>
<tr>
<td>Bias</td>
<td>-2.07</td>
<td>-0.44</td>
<td>-0.34</td>
<td>-1.17</td>
<td>-0.97</td>
<td>-0.51</td>
<td>-0.27</td>
</tr>
<tr>
<td>MAE</td>
<td>2.08</td>
<td>0.47</td>
<td>0.35</td>
<td>1.19</td>
<td>0.98</td>
<td>0.54</td>
<td>0.29</td>
</tr>
<tr>
<td>RMSE</td>
<td>4.47</td>
<td>1.62</td>
<td>1.31</td>
<td>3.08</td>
<td>2.55</td>
<td>1.71</td>
<td>0.29</td>
</tr>
<tr>
<td>FSE</td>
<td>1.07</td>
<td>0.49</td>
<td>0.32</td>
<td>0.94</td>
<td>0.78</td>
<td>0.52</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Table 13 Overall error scores computed for hourly cumulated rainfall and for the Nearest value radar-raingauges spatial coupling.

8. SENSITIVITY ANALYSIS TO DATA QUALITY

A sensitivity analysis (SA) to data quality is introduced with the purpose to investigate the influence of different quality indexes associated to the radar precipitation, on raingauges comparison.

The scatter plot is the method chosen in this sensitivity analysis which is not 'pass / fail' evaluation, but rather informative analysis. Three quality index thresholds (0.6, 0.7 and 0.8) were selected and each of the relative precipitation was compared with the corresponding values measured by raingauges.

The sensitivity analysis was carried out on the Manaus and Vale do Paraiba campaigns using the entire data set based on hourly rainfall accumulations. The methodology employed to analyze the data is focused on R2 and on polarimetric rainfall algorithms which overall provided the best scores between the error indices: Rq2, Rk2, and Rq2Vu15.

Figure 51 shows the scatter plots between radar and raingauges using the Manaus data set for different rainfall estimators and aggregating the data according to the quality index. This consists of 384 hourly rainfall accumulations, of which only 77 exceed the precipitation threshold of 0.2 mm (which is the minimum threshold detectable by the rain gauge) and all have a quality index higher than 0.8. This is due to the proximity of the rain gauges to the radar site (less than 10 km).
Figure 51. Scatter plot of \( R_{q2} \)-gauges (top left), of \( R_{k2} \)-gauges (top right), of \( R_{z} \)-gauges (bottom left), and of \( R_{q2}Vu15 \)-gauges (bottom right) hourly cumulated and quality indexes related for the events occurred in Manaus between February and March 2014.

Despite the low number of samples analyzed, the graph shows a high correlation in all the estimators, as confirmed by the scores in Table 13 (reproduced hereafter) and particularly with the \( R_{q2}Vu15 \) model.

<table>
<thead>
<tr>
<th>Nv</th>
<th>( R_{z} )</th>
<th>( R_{k2} )</th>
<th>( R_{q2} )</th>
<th>( R_{q2}Vu15 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corr</td>
<td>0.79</td>
<td>0.97</td>
<td>0.92</td>
<td>0.98</td>
</tr>
<tr>
<td>Bias</td>
<td>-2.07</td>
<td>-0.34</td>
<td>-0.97</td>
<td>-0.28</td>
</tr>
<tr>
<td>MAE</td>
<td>2.08</td>
<td>0.35</td>
<td>0.99</td>
<td>0.29</td>
</tr>
<tr>
<td>RMSE</td>
<td>4.47</td>
<td>1.31</td>
<td>2.55</td>
<td>1.15</td>
</tr>
<tr>
<td>FSE</td>
<td>1.07</td>
<td>0.32</td>
<td>0.63</td>
<td>0.29</td>
</tr>
<tr>
<td>MRB</td>
<td>0.50</td>
<td>0.91</td>
<td>0.76</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Table 14 Overall error scores computed for hourly rainfall accumulations and for the Nearest value radar-raingauges spatial coupling using the Manaus data set.

Figure 52 shows the scatter plot between radar and raingauges using the Vale do Paraiba data set for different rainfall estimators and aggregating the data according to the quality index. This data set consists of 1176 hourly rainfall accumulations, of which only 155 exceed the raingauges precipitation threshold of 0.2 mm, while 74 have quality index greater than 0.8.
Figure 5.2. Scatter plot of $R_q$-gauges (top left), of $R_K$-gauges (top right), of $R_Z$-gauges (bottom left), and of $R_{q Vu15}$-gauges (bottom right) hourly cumulated and quality indexes related for the events occurred in Vale do Paraíba between November and December 2011.

Figure 5.3 shows the scatter plot of accumulated with quality index $Q$ greater than 0.8 for different rainfall estimators and colored according to the density of the points. The results for the scatter show a high correlation.
Figure 53. Scatter plot of $R_q$-gauges (top left), of $R_K$-gauges (top right), of $R_Z$-gauges (bottom left), and of $R_q$Vu15-gauges (bottom right) hourly cumulations having quality index $Q \geq 0.8$ for the Vale do Paraiba dataset.

The values of the different statistics for all the methods can be found in Table 15 divided by quality index. The combined polarimetric rainfall algorithms ($R_q$ and $R_q$Vu15) are closely related to $R_Z$ and $R_K$ and therefore have similar error scores, which improve by increasing the quality index $Q$.

<table>
<thead>
<tr>
<th></th>
<th>Q≥0.6</th>
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<th>Q≥0.8</th>
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</thead>
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<tr>
<td></td>
<td>$R_Z$</td>
<td>$R_K$</td>
<td>$R_q$</td>
</tr>
<tr>
<td>Corr</td>
<td>0.94</td>
<td>0.97</td>
<td>0.97</td>
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<tr>
<td>Bias</td>
<td>-0.78</td>
<td>-0.41</td>
<td>-0.59</td>
</tr>
<tr>
<td>MAE</td>
<td>0.80</td>
<td>0.54</td>
<td>0.69</td>
</tr>
<tr>
<td>RMSE</td>
<td>2.46</td>
<td>1.99</td>
<td>2.51</td>
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<tr>
<td>FSE</td>
<td>0.67</td>
<td>0.54</td>
<td>0.69</td>
</tr>
<tr>
<td>MRB</td>
<td>0.79</td>
<td>0.89</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Table 15 Overall error scores computed for hourly cumulated rainfall with Q≥0.6, Q≥0.7, Q≥0.8 and for the Nearest value radar-raingauges spatial coupling.
CONCLUSIONS

This work has analyzed the data collected by mobile X-band polarimetric radar during the CHUVA project, held in Brazil between 2011 and 2014. The related on ground rainfall estimates and associated quality index was provided to constraint the validation of the H-SAF precipitation products.

The current polarimetric processing chain attempts to correct for the contributions of the different sources of uncertainty and provide the estimation of the reflectivity ($Z_h$) and the specific differential phase ($K_{dp}$), which contain the microphysical information required to perform attenuation correction and quantify the precipitation rate. At the same time, the quality of the polarimetric variables was evaluated and supplied as a product to be used as a constraint within the validation activity.

Different polarimetric QPE algorithms have been coded and evaluated at the hourly time step using independent rain-gauges. Three days of observations, from the campaign at Fortaleza in 2011, were used for the evaluation. The algorithms that have been tested are: simple Z-R relationship (Marshall-Palmer, 1948) indicated as $R_Z$, algorithms based on $K_{dp}$ solely ($R_{K1}$ and $R_{K2}$), algorithms based on combination of $K_{dp}$ and $Z_h$ whose weights are the quality indices $q_{loss}$ and $q_{noise}$ ($R_{q1}$ and $R_{q2}$), and algorithms based on combination of $K_{dp}$ at medium-high $K_{dp}$ (above 0.5° km$^{-1}$) and attenuation-corrected $Z_h$ at low $K_{dp}$ (below 0.5° km$^{-1}$) ($R_{q1V15}$ and $R_{q2V15}$).

The analysis of the results carried out confirms the benefits brought by polarimetry to quantitative rainfall rate estimation with radar, and seems to indicate, considering the problems of a possible radome attenuation, here not considered in the processing chain, that the algorithm which best estimates the precipitation intensity is $R_{q2V15}$.

Although $R_{K2}$ has provided equally good results, $R_{q2V15}$ has better performance both for low and for higher precipitation. This algorithm obtains an overall correlation higher than 0.98 and in terms of bias also gets a good score with a value within 0.34. Other indicators (RMSE and FSE) also confirm the goodness of this algorithm with respect to all other employees in the evaluation. In addition, the adopted quality scheme seems to impact the validation results as perceived by the sensitivity analysis to data quality.
10. REFERENCES


