Operational use of dual-polarisation: lessons learned at Météo France after 8 years of experience at all wavelengths (S / C / X)

Pierre Tabary
Centre de Météorologie Radar, Météo France, Toulouse, France
42, avenue Coriolis 31057 Toulouse
Tel.: +33 5 61 07 95 20
Email : pierre.tabary@meteo.fr

Abstract

Météo France investment on operational radar polarimetry started 8 years ago with the installation, in 2004, of the first French polarimetric radar (C-band) in Trappes, near Paris. Since then, a huge amount of work has been carried out and the positive results obtained have led to the extension of dual-polarization to other radars of the network, which in 2012 will count 16 operational polarimetric elements at the three weather radar wavelengths (11 at C-band, 3 at S-band and 2 at X-band).

After several years of development, a first version of operational polarimetric chain was finally introduced on all French polarimetric radars in 2011 - 2012, with clear positive impacts on non meteorological echo identification and quantitative precipitation estimation (QPE), especially at high rain rates.

This paper will provide a broad overview on 1) the data quality monitoring procedures that have been designed and implemented, 2) the assessment of the benefits brought by polarimetry to existing products (e.g. rain rate estimation) at the three wavelengths and 3) the perspectives of new products (e.g. hydrometeor classification), 4) the challenges that are still ahead (management of a network of polarimetric and non polarimetric radars, interaction between polarimetric rain rate estimators and conventional rain gauge adjustment schemes, calibration of polarimetric variables).
1. Introduction

Accurate rainfall estimation is fundamental for many applications in hydrology, nowcasting, etc. Weather radars are the most adequate instruments to reveal the high resolution spatial and temporal variation of the rainfall fields and their potential value for Quantitative Precipitation Estimation (QPE) was recognized since practically the beginning of the field (Marshall et al. 1947). However, radar measurements are subject to multiple uncertainty sources which can roughly be grouped in three categories (Zawadski 1984): 1) Errors related to the radar system itself (calibration biases, antenna positioning errors, etc.), 2) Errors related to the interaction between the radar signal and the environment (clutter, partial beam blocking, attenuation (PBB), etc.) and 3) Ambiguity of the relation between radar measurement and surface rainfall accumulation (precipitation type, non-uniform vertical profile of reflectivity (VPR), drop size distribution variability, etc.).

A continuous effort by the entire weather radar community has been placed in quantifying and mitigating these sources of error. A comprehensive review is out of the scope of this article but we can cite works on ground clutter identification (Joss and Lee, 1995, Sugier et al. 2002), PBB correction (Delrieu et al. 1995) or VPR correction, (Koistinen, 1991, Kitchen et al. 1994, Andrieu and Creutin, 1995, Germann and Joss, 2002).

The first operational Météo France radar rainfall product dates from 1997. Since then, the demand by end users has resulted in an increase of both the number of radar systems and the complexity of the signal processing up to reaching the product described hereafter (see Tabary 2007).

The recent advent of polarimetry has opened new perspectives since the extra information provided by polarimetric variables can significantly help mitigating errors (Bringi and Chandrasekar 2001). It enables identification of the scatterers, attenuation correction, and real-time retrieval of the DSD parameters. Numerous polarimetric QPE algorithms have been proposed at S, C and X-band (see Rhyzhkov et al. (2005), Tabary et al. (2011) and Figueras i Ventura et al. (2012a)).

Despite the fact that the first studies on polarimetric QPE date from the 70s (For example that of Seliga and Bringi, 1976) up to very recently polarimetric radars were used mainly in the atmospheric research domain and not in the operational weather radar networks. Some examples (among others) to illustrate the extension towards operations: the American National Weather Service is currently upgrading its S-band weather radar network to polarimetry (Cocks et al., 2012). In Europe, C-band radars are much more common. Several Weather Services have recently upgraded (Finish Meteorological Institute, various Italian regional services) or are upgrading (UK Met Office, Deutscher Wetterdienst) part or all of its weather network (Figueras i Ventura et al. 2012b). In Japan there exists an operational X-band polarimetric radar network for weather surveillance in densely inhabited areas (Maesaka et al., 2011).

The operational deployment of polarimetry is complex: regardless of the hardware upgrade, accurate monitoring techniques have to be implemented, personnel and end-users have to be trained, the co-existence of polarimetric and non-polarimetric radars has to be dealt with etc. More importantly, the theoretical capabilities of polarimetry have to be revisited taking into account realistic assumptions on the quality of polarimetric variables estimated by operational scanning radars.

The first Météo France polarimetric radar was installed in 2004 in Trappes, near Paris. The installation was followed by a long period of research and development (see Figueras i Ventura et al. (2012a) for an overview) which finally resulted in a first version
of a polarimetric pre-processing chain introduced into operations in February 2012. This first version basically corrects for precipitation-induced attenuation the radar reflectivity ($Z_h$) using the differential phase ($\phi_{dp}$). The metropolitan French radar network is illustrated in the Figure below:

![Figure 1](image)

The encouraging results obtained led to the development of a second version of the polarimetric radar rainfall product, which further enhances the use of polarimetric data. In a first step a long term data quality analysis of the S and C band radars was undertaken to verify the feasibility of using polarimetric variables for quantitative measurements. It followed a test in semi-ideal conditions (PBB free areas, rain-only events, single-tilt) at C-band of several polarimetric QPE algorithms to determine the optimal. A hybrid Z-R $K_{dp}$-R algorithm was considered the best choice. The research is described in detail in Figueras i Ventura et al. (2012a). This algorithm is implemented in the second version of the operational polarimetric radar rainfall product.

This paper objectively evaluates the performance of each radar rainfall product: mono-polar, first polarimetric version and second polarimetric version at the three frequency bands used at Météo France: S, C and X. It therefore provides useful information on what improvement on performance can be expected from the operational use of polarimetry and valuable insight on the added capability of polarimetry at each frequency band.
The paper is structured as follows: Section 2 summarizes the current operational radar rainfall products for both single polarization and polarimetric radars. Section 3 describes the second version of the polarimetric radar rainfall product. Section 4 analyses the differences between the new and old quality indexes used to combine the radar data, Section 5 analyses the results of the objective evaluation of the 3 products at S-, C- and X-band performed using rain gauge data. Conclusions and future developments are discussed in Section 6.

2. Monitoring the quality of polarimetric variables

The polarimetric chain provides several monitoring variables that are essential indicators of the quality of the radar system and its data.

- **Daily-averaged $\rho_{hv}$ value in rain.** It is calculated from average $\rho_{hv}$ values per elevation angle right after the bright band is determined. To be included in the computation, measurements must be below the bright band and with a reflectivity value between 20 and 40 dBZ. A value of 0.99 is expected.
- **Daily-averaged azimuth-dependent $\Phi_{dpo}$ curve for each elevation and for all elevations put together.**
- **Daily-averaged azimuth-dependent Z$_{dr}$ bias curve for each elevation and for all elevations put together.** This is calculated from the median of rain-classified gates with $Z_h$ value between 20 and 22 dBZ, where the expected Z$_{dr}$ value is 0.2 dB (see Tabary et al., 2011). Several constraints are imposed (regarding attenuation, $\rho_{hv}$, number of valid points etc.) to minimize the uncertainty of the measurement.
- **Daily-averaged Z$_{dr}$ bias at 90° elevation in precipitation.** A 90° scan every 15' is included in the scanning strategy of all Météo France polarimetric radars. The expected value is 0 dB. This value is obtained from the median of the range gates situated between 2 and 6 km which can be assumed to be precipitation. At the end of the day the weighted average of all the valid 90° elevation scans is calculated.
- **Solar monitoring variables following the method described in Holleman et al. (2010).** The method provides the daily azimuth and elevation antenna position biases with respect to the theoretical sun position, as well as the daily receiver Z$_{dr}$ bias and the average sun power $P_{sun}$ at horizontal polarization.

The Figure below illustrates different $\Phi_{dpo}$ patterns corresponding to different radomes:
The temporal evolution of the offsets / biases on $\Phi_{DP}$ and $Z_{DR}$ and $\rho_{HV}$ is illustrated for the Avesnes (C-band) radar over more than 1 year:
Finally, the monitoring indicators are used to trigger alarms on a daily basis and switch from DPOL to SPOL. See below:

3. Current Operational Radar Rainfall Product
The current operational weather radar network (in June 2012) at metropolitan France is composed of 24 radars. Most of the radars are C-band but there are 6 S-band radars in the South of France, which, due to the Mediterranean climate, are more exposed to extreme precipitation events. The network is being gradually upgraded to polarimetry. At the moment there are 13 polarimetric radars in the network, 11 at C-band and 2 at S-band. It is expected that by 2020 all radars in the network will be polarimetric. The exploitation mode of each radar consists on a supercycle repeated every 15' divided in 5' cycles. In each cycle, 4 to 6 scans at different elevation angles (depending on the orography) are performed. The lowest tilts, optimal for hydrological applications, are revisited every 5'.

In addition to the operational radars, there are 2 X-band radars in the French Alps in the framework of the Rhytmme project (Kabeche et al., 2012). These radars are used as gap fillers. Within the Rhytmme project a network of 4 radars is planned. At the moment Météo France has deployed one radar. The other one is a pre-existing HYDRIX radar owned by the CNRS and operated by NOVIMET. Due to the co-existence of polarimetric and non-polarimetric radars in the network, the operational radar rainfall products has two operational modes: one that makes use of polarimetry and one that does not.

**a. Operational Radar Rainfall Product**

The processing chain of the conventional single polarization radar was described in detail in Tabary (2007). A few changes have been introduced since that paper was published. For convenience we summarize in the following the main processing steps. The modules introduced since the publication of Tabary (2007) are discussed in more detail. The flow diagram of the algorithm can be seen below:

![Flow diagram of the operational radar rainfall product. Polarimetric modules are identified by the grey italics.](image)

The processing is performed on $Z_h$ data in Cartesian coordinates with 1 km² pixel resolution, obtained at each scan. During the processing a quality index matrix (1 for perfect measurement, 0 for not usable pixel) for each scan is generated.
**Clutter identification:** In Tabary (2007) ground clutter (GC) identification is exclusively performed based on a threshold on the pulse-to-pulse fluctuation of the radar reflectivity $\sigma_z$. The threshold level $\sigma_{zo}$ depends on the measurement conditions. In areas of permanent GC, the threshold is more restrictive. A new condition has been added whereby the threshold is also more restrictive if Doppler velocity is very low, hence likely to correspond to GC. Moreover, the pixels around a pixel identified as GC are substituted by the average of the surrounding valid pixels. If no surrounding pixel is valid, the pixel is considered to be GC. Additionally, pixels which are statistically contaminated by windmill echoes or sea clutter echoes or that have a $Z_h$ texture above a threshold are classified as GC.

**PBB Correction:** The $Z_h$ value is corrected according to a PBB static map. In addition to the method based on wave propagation simulations using orographic maps described in Tabary et al. (2007), long-term rainfall accumulations are used to account for PBB caused by man made structures and trees.

**VPR Correction:** As described in Tabary et al. (2007), VPR is computed from ratios of hourly rainfall accumulation at different elevations in collocated pixels. Such ratios are used to determine the optimal VPR from a set of pre-defined VPR models.

**Gas-induced attenuation correction:** Absorption by atmospheric gases leads to $Z_h$ attenuation (Doviak and Zrnic, 1992). The gas-induced attenuation depends on the wavelength and the altitude above sea level. This module estimates the gas attenuation assuming a standard atmosphere and corrects for it.

**Synchronization:** The scans performed during the 5’ cycle are synchronized before combination at the end of the 5’ cycle using the advection field. The advection field is calculated by analyzing the displacement between the current $Z_h$ composite image and the one from the previous cycle using the cross-correlation approach describe by Tuttle and Foote (1990).

**Weighted Linear Combination:** The best estimation of $Z_h$ on the ground is obtained by combining the measurements performed at different elevations in collocated pixels weighted according to their quality indexes. The value of the maximum quality index is kept as a measure of the quality of the multi-tilt QPE.

**Reflectivity to Rainfall Rate Conversion:** $Z_h$ is converted into rainfall rate using the Marshall-Palmer $Z$-$R$ relationship.

**5’ Rainfall Accumulation:** The same advection field used in the synchronization is re-used to oversample the data to 1’ temporal resolution. The 5 rainfall fields obtained are added on a pixel basis in order to get the 5’ rainfall accumulation. Areas of missing data are filled by extrapolating, still with the advection field, the previous 5’ rainfall accumulation.

**Rain Gauge Adjustment:** Despite all the corrections radar rainfall accumulations still suffer sometimes from non negligible biases with respect to rain gauge ground measurements (Fulton et al (1998), Anagnosotu and Krajewski (1999)). In order to minimize those biases rain gauge data is used to correct the 5’ radar rainfall accumulation field. The adjustment scheme consists in applying one single adjustment factor (AF) to the entire 5’ radar 1 km$^2$ Cartesian QPE map. The method to obtain AF is described in detail in Tabary et al. (2011).

**b. Polarimetric Modules of the Operational Radar Rainfall Product**

The polarimetric data processing chain which is described in detail in Figueras i Ventura et al. (2012a). The processing chain performs several corrections to the raw polarimetric variables and provides several parameters, notably the echo type and the path integrated attenuation (PIA) in 1 km$^2$ resolution Cartesian coordinates, as well as several monitoring parameters.
As it can be seen below, the inputs of the polarimetric chain are the polarimetric variables in high-resolution polar coordinates (240 m x 0.5°).

![Figure 6: The polarimetric processing chain.](image)

They sequentially undergo a differential reflectivity ($Z_{dr}$) calibration, a non-meteorological echo classification, a bright band identification based on the co-polar correlation coefficient ($\rho_{hv}$), a dynamic correction of the system $\phi_{dp}$ offset and $\phi_{dp}$ median filtering, the estimation of the specific differential phase $K_{dp}$, the attenuation correction of $Z_h$ and $Z_{dr}$, and the hydrometeor classification by a fuzzy logic algorithm using the polarimetric variables, the bright band altitude and thickness and the temperature. However at the moment only two of the outputs are exploited operationally in the rainfall product, the estimated attenuation and the Clear Air (CA) identification. The decision to only use a fraction of the potential of polarimetry in a first phase has several motivations. In the first place, since polarimetry is a relatively new concept, there is a need to gradually introduce it to end users and maintenance teams. In the second place, each time a new polarimetric variable is used the downstream processing must be upgraded and time is needed to perform the upgrade.

**CA identification:** CA identification is performed by using the echo type determined by the polarimetric chain. The polarimetric chain has a pre-classification module that discriminates between CA, GC and Precipitation and noise and missing data. The classification is based on a fuzzy logic algorithm that uses the probability density functions of $\rho_{hv}$, $\sigma_z$ and the $Z_{dr}$ texture of each of the three echo types (Gourley et al, 2007a). In the first version of the polarimetric chain it was decided to use only the CA identification and keep the legacy GC identification schemes of the single polarization chain. $Z_h$ of pixels identified as CA by the polarimetric chain is simply set to 0 mm$^6$m$^{-3}$ whereas the Quality Index is kept unchanged.

**Precipitation-induced Attenuation Correction:** The PIA in precipitation is considered to be linearly proportional to $\phi_{dp}$. The constant of proportionality $\gamma_h$ varies according to the wavelength. The coefficient at C-band was determined empirically using data from the Trappes radar (see Gourley et al. 2007b) to be 0.08 dBdeg$^{-1}$. The S-band coefficient was taken from Bringi and Chandrasekar (2001): 0.004 dBdeg$^{-1}$. The coefficient at X-band was extracted from joint S-band /X-band measurements (see Tabary et al. 2008): 0.28 dBdeg$^{-1}$. 
The aforementioned polarimetric modules are placed between the Clutter Identification and the PBB Correction of the single polarization chain. The rest of the processing chain is left unchanged.

4. Second Version of the Polarimetric Radar Rainfall Product

The new polarimetric radar product aims at improving the performance in three major aspects: better echo classification, better precipitation estimation and a lower detectability threshold. It also paves the way towards higher spatial resolution products (250m) by performing most of the data processing in high resolution (0.5°x240m) polar coordinates and to the retrieval of vertical profile of equivalent liquid water precipitation rates by treating separately each hydrometeor type. The echo classification is now fully performed by the polarimetric chain. The necessary corrections on \( Z_h \) at each individual scan are also performed by the polarimetric chain with the aim of having the best quality polarimetric variables entering into the hydrometeor classification. Based on that, several modules have been added to the polarimetric chain.

**Extra noise filtering:** The noise filtering in the previous products is performed by finding the minimum \( Z_h \) per scan and adding a certain margin to account for the noise standard deviation. It has been recognized that emission from ground clutter results in an increase in the noise floor, which is spatially dependent. Therefore the new noise filter finds the minimum at far range per ray.

**PBB \( Z_h \) correction:** The procedure is exactly the same as previously described. The only difference is that the correction is performed in high resolution polar coordinates instead of Cartesian coordinates.

**Gas-induced attenuation correction:** Again, the difference is that the correction is performed in polar coordinates.

**Ground clutter detection using a static ground clutter map:** Polarimetric variables may not be usable either due to hardware or transmission problems or because the signal to noise ratio is too low. A very restrictive threshold of 15 dB SNR has been set on the use of polarimetry to ensure high quality polarimetric data. In such case the ground clutter detection is performed using a threshold on \( \sigma_z \). Areas of frequent ground clutter have a more restrictive threshold. The ground cluttered areas have been determined a priori by observing the median values of \( Z_h \) over an entire non-precipitating day.

**Quantitative precipitation estimation QPE:** The rainfall rate is estimated differently according to the echo type. Solid precipitation (snow, ice, etc.) is estimated using a Z-R relationship where \( Z_h \) has been attenuation corrected. In areas where polarimetry was not available (e.g. low SNR), \( Z_h \) is also converted into rainfall rate using a Z-R relationship. For the quantification of rain a hybrid estimator is used. If \( K_{dp} \) is above a certain threshold a \( K_{dp} \)-R relationship is applied, otherwise a Z-R relationship is used. Notice that \( Z_{dr} \) is not used in the QPE because its current stability was considered insufficient (See Figueras i Ventura et al, 2012a). The threshold is based on the \( K_{dp} \) value because it is insensitive to attenuation, calibration errors and PBB. At the moment the Z-R relationship used for all the estimators is the Marshall-Palmer. Below the threshold level, \( K_{dp} \) is considered to be too noisy to be used. The \( K_{dp} \)-R relationship used at S and C bands is the Beard and Chuang (1987) and it is used for \( K_{dp} \) above 1°km\(^{-1}\). Studies at X-band by Kabeche et al. (2012) found that the Brandes et al. (2002) \( K_{dp} \)-R relationship is more suitable at X-band and that above 0.5°km\(^{-1}\) \( K_{dp} \) is sufficiently clean to be usable.

**Polar to Cartesian coordinates conversion:** The legacy processing is performed on \( Z_h \) in Cartesian coordinates. The rainfall rate output of the polarimetric chain is
converted into 1 km² Cartesian coordinates using the nearest neighbour approach and back to $Z_h$ using the inverse Marshall-Palmer Z-R relationship.

Reflectivity detectability threshold: It is a common assumption, yet sometimes wrong, to consider that pixels at noise level correspond to valid, no-rain areas. In presence of attenuation, and specially at short wavelength, this is clearly a wrong assumption. The precipitation detectability depends on the sensitivity of the radar but also on the presence of PBB, on the level of ground clutter and the attenuation suffered by the signal. It is therefore a space-time varying parameter. The precipitation-induced attenuation in particular increases with the radar frequency. It is therefore important to inform the user of the minimum rainfall rate detectable since, when severe convective cells are present, precipitation further away may not be detectable by the radar. It is also an important parameter to determine up to which distance from the radar low $Z_h$ phenomena like fog can be detected. Furthermore this is essential information when performing multi-radar combination (Maesaka et al., 2011).

The new radar product provides an information of $Z_h$ detectability together with the 5' rainfall accumulation. The module estimates the detectability of each scan in the 5' cycle by taking into account the noise level, the PBB, the gas and precipitation induced attenuation and the $Z_h$ level of the detected ground clutter. The detectability of precipitation on the ground is then considered to be the minimum detectable $Z_h$ of all collocated measurements at the vertical below 10 km.

5. Old and New Quality Indexes

The quality index is used as an indicator of the confidence on the measurement at pixel level. The quality index at pixel level determines the weight that the measurement has in the multi-tilt combination. The maximum of the quality indexes in a multi-tilt combination is a qualitative indicator of the uncertainty of the measurement on the ground. It is used to determine the weight of the pixel when performing the multiple radar composite.

The quality index of the operational radar rainfall product depends on the echo classification, the estimated percentage of beam blockage and the altitude of the measurement. The dependency is linked to the uncertainty in the corrections performed. If the PBB or VPR corrections were to be perfect they would not impact the quality index. This dependency is expressed as follows:

$$\omega(x,y) = \omega_{GC}(x,y) \omega_{PBB}(x,y) \omega_{h}(x,y)$$

$\omega_{GC}$ is one when the pixel is classified as precipitation or its $Z_h$ is below 8 dBZ and 0 otherwise.

The dependence with the percentage of PBB is considered linear and can be expressed as follows:

$$\omega_{PBB}(x,y) = \begin{cases} 0 & PBB(x,y) \geq 70 \\ \frac{PBB(x,y)}{100} & PBB(x,y) < 70 \end{cases}$$

The dependence with height above the ground is considered exponential of the form:
\[
\omega(x,y) = \begin{cases} 
0 & h(x,y) - h(x,y) \leq 10 \text{km} \\
\frac{e^{-\frac{h(x,y) - h(x,y)}{h(x,y) - h(x,y)}}}{0} & h(x,y) - h(x,y) \geq 10 \text{km}
\end{cases}
\]  

(2)

Where \( h_0 \) is the altitude of the ground above sea level, \( h \) is the altitude of the measurement above sea level and \( h_0 = 0.5 \text{ km} \).

Examples of quality codes are given below:

![Figure 7: Example of 5' rainfall accumulation and associated quality index.](image)

The event occurred in Trappes the 14th July 2010 at 11:55 am UTC. Left column correspond to DBP1, right column to DBP2. Quality code decreases with distance as a consequence of the increased elevation of the radar beam and with PBB. Notice the low quality code spots close to the radar, which correspond to areas of clutter where a higher tilt is predominant in the composite.

The second version of the polarimetric radar rainfall product adds the dependence on Path Integrated Attenuation (PIA):

\[
\omega(x,y) = \omega_{\text{PIA}}(x,y) \omega_{\text{PBB}}(x,y) \omega_{\text{KDP}}(x,y) \omega_{\text{KDP}}(x,y)
\]

Where:

\[
\omega_{\text{PIA}}(x,y) = \begin{cases} 
1 & \text{PIA}(x,y) < \text{PIA}_0 \\
0 & \text{PIA}(x,y) \geq \text{PIA}_0
\end{cases}
\]

(3)

The weight is kept to 1 when rainfall rate is estimated using \( K_{\text{dp}} \) since it is insensitive to precipitation attenuation. \( \text{PIA}_0 \) is set to 40 dB. For the same reason, \( \omega_{\text{PBB}} \) is modified as follows:

\[
\omega_{\text{PBB}}(x,y) = \begin{cases} 
1 & \text{PBB}(x,y) < 70 \\
0 & \text{PBB}(x,y) \geq 70
\end{cases}
\]

(4)
Finally, $\omega_{OC}$ is kept to 0 if ground clutter is identified, regardless of the $Z_h$ value.

Admittedly, the formulation of the weight dependency with respect to PIA is at the moment rather arbitrary. Studies at X-band (Tabary et al., 2008) showed that the PIA standard deviation is linearly constant in relative terms and therefore the error committed in its estimation is linearly increasing. The rather high PIA$_o$ threshold is a trade off between the need to reflect the increase of uncertainty in the measurement due to PIA while at the same time allowing the use of highly attenuated data at X-band. A more specific study on the optimal formulation of the PIA dependency at different wave lengths is required but it is out of the scope of this paper. However it should be noticed that the most significant impact of the PIA weight is in the multi-radar composite.

Fig. 7.d) shows an example of the new quality code for the same event as the one showed in Fig. 7.c). Comparing the two images the difference in quality code can be appreciated. In Fig. 7.d) there are more spots close to the radar because the GC identification criteria is more strict. The use of $K_{dp}$ results in a higher quality index in areas of PBB (see the area west of the radar). On the other hand, in areas with large attenuation, where $Z_h$ is used (just behind the convective cells) to obtain the rainfall rate, the quality code is lower.

6. Products Evaluation

a. Data selection and Evaluation methodology

The three radar rainfall products: the single polarization (hereafter CONV), the first version of the polarimetric chain (hereafter DBP1) and the second version of the polarimetric chain (hereafter DBP2) have been evaluated off-line using several precipitation episodes. The final Météo France product is adjusted using rain gauges but in order to strictly evaluate the performance of the processing chain data before the rain gauge adjustment has also been analyzed.

The 5' rainfall accumulation estimated by the radar is hourly accumulated using a very strict criteria whereby if one of the 12 pixels in the time series is not valid within the hour the hourly accumulation is set to data not available. Unlike the other products, DBP2 invalidates pixels containing ground clutter with very low $Z_h$. For this reason a slightly different criterion has been taken to validate the hourly accumulation. In that case, if a maximum of 2 pixels are invalid but they have a $Z_h$ threshold below 5 dBZ the invalid pixels are set to have a 0 mm rainfall accumulation and the hourly accumulation is considered valid.

The hourly rainfall accumulations are compared against hourly rain gauges. The Météo France rain gauge network consists of tipping bucket gauges with a bucket resolution of 0.2 mm, i.e. the minimum hourly rainfall accumulation that can be measured is 0.2 mm. All rain gauge data are routinely quality-controlled as described in Figueras i Ventura et al. (2012a). The radar-rain gauge comparison is done by matching each rain gauge with the corresponding radar pixel.

The quality of the algorithms is evaluated using the normalized bias (NB) between the rain gauge and the radar rainfall accumulation defined as:

$$NB = \frac{\langle R \rangle}{\langle G \rangle} - 1$$ (5)

where <> denotes the average, the correlation (corr):
the root mean square error (RMS):

\[ \text{RMS} = \sqrt{\frac{\sum_{i} (R_i - G_i)^2}{n}} \]  \hspace{1cm} (7)

and the Nash-Sutcliffe model efficiency coefficient (Nash):

\[ \text{Nash} = 1 - \frac{\sum_{i} (R_i - G_i)^2}{\sum_{i} (R_i - \langle G \rangle)^2} \]  \hspace{1cm} (8)

In addition, the dispersion defined as the percentage of radar-rain gauge ratios outside the interval 0.8-1.25 has also been calculated.

The present study is focused on a warm period, where the benefits of the polarimetric QPE are more relevant. The selection of events is performed objectively using three criteria. Firstly, the daily average ground temperature close to the radar must be high enough so that the radar beam was below the freezing level height at 60 km. A standard atmosphere temperature decrease of \(-6^\circ/\text{km}\) is used to estimate the altitude of the freezing level height. Secondly, a significant amount of rain must be present in the vicinity of the radar. The amount of rain is determined by calculating the average daily rainfall accumulation of all the rain gauges within a 60 km radius area. Events with an average rainfall accumulation higher than 5 mm are considered. Finally, all the selected events should have been observed using the same scan strategy.

For S and C band, data from the year 2010 is analysed. At C band four different radars out of the nine present that year from different regions and with different characteristics are used. They are considered to be representative of the entire radar network. For the evaluation at S band events observed by the Nimes radar, the sole S band radar in the network in 2010, are analyzed. The X band radar is analyzed using data from Maurel, which has a raw data processor similar to the one used by the radars in the operational network (Parent-du-Châtelet et al., 2001). Data from Maurel is available since the second half of 2011. Table 1 lists the radar-event couples that result from the selection.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Radar</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-band</td>
<td>Nimes</td>
<td>6, 7 Sept, 9, 10 July 2010</td>
</tr>
<tr>
<td>C-band</td>
<td>Avesnes</td>
<td>12, 14 July 15, 16, 26 Aug 2010</td>
</tr>
<tr>
<td></td>
<td>Blaisy</td>
<td>21, 22 July, 15, 16, 23, 27 Aug 7 Sept 2010</td>
</tr>
<tr>
<td></td>
<td>Montancy</td>
<td>28, 29 July, 2, 5, 12, 14, 15, 16, 24, 27 Aug 2010</td>
</tr>
<tr>
<td></td>
<td>Trappes</td>
<td>3, 12, 14 July 15 Aug 2010</td>
</tr>
<tr>
<td>X-band</td>
<td>Maurel</td>
<td>27 July, 7 Aug, 4 Sept, 4 Nov 2011</td>
</tr>
</tbody>
</table>

**Table 1.** Events used for the evaluation.
b. General results

The results are stratified according to three threshold on the rain-gauge hourly accumulations: >0.2 mm (all rainfall accumulations, AR), >1 mm (moderate and high hourly accumulations, MR) and >5mm (intense hourly accumulations, IR). The results are obtained in the area 60 km around the radar, which have the best hydrological visibility.

1). RESULTS AT S-BAND

The global results obtained by each rainfall product are represented in Fig. 8.

Figure 8. Results of each product without rain gauge adjustment (left hand side of panel) and with rain gauge adjustment (right hand side) at S band.
The evaluation is performed before and after the rain gauge adjustment in order to clearly determine the impact of the different ways to process the data on the results. As it can be seen in Fig 8.a) the CONV product slightly underestimates precipitation (NB=-0.13 for AR). The underestimation is more pronounced at IR (NB=-0.27). As it is shown in Fig. 8.b), the rain gauge adjustment is able to globally correct for such underestimation but intense precipitations remain underestimated (NB=-0.13). The use of the DBP1, which basically corrects for precipitation-induced attenuation results in an improvement of NB and corr as shown in Fig. 8.c). Such improvement is even more relevant at IR (NB reduced from −0.27 to −0.18) as shown in Fig. 8.d). The rain gauge adjustment is less dramatically beneficial for the DBP1 and the final results are comparable with those obtained by the CONV product. Nevertheless minor improvements respect to CONVadj should be signaled. As represented in Fig. 8.e), DBP2 obtains the best score in all categories. Particularly remarkable is the NB at IR which is reduced by 1/3 compared to that of CONV. The application of the rain gauge adjustment, though, does not significantly improve the results, as shown in Fig. 8.f).

2). RESULTS AT C-BAND
The global results at C-band are represented in Fig. 9.
As it can be seen in Fig. 9. a) the radar largely underestimates precipitation (-0.32 for AR and up to –0.47 for IR). Corr is rather poor as well for IR. This large underestimation can be attributed to precipitation-induced and radome-induced attenuation but miscalibration of $Z_h$ should not be discarded. The rain gauge adjustment significantly reduces NB (down to –0.10 for AR and –0.28 for IR) and it has a positive impact also on corr (and increase of 0.04 in the score) (see Fig. 9.b). The positive impact of the attenuation correction of DBP1 is readily visible in Fig. 9.c). NB for AR is reduced to –0.25 but the most positive impact is, as expected, in IR, where both NB and corr are greatly improved (NB down to –0.34 and corr up to 0.70). With the rain gauge adjustment a similar score in terms of NB to CONVAdj is obtained but corr is further improved (See Fig. 9.d). Again, the best score is obtained by DBP2, with the most remarkable improvement on the IR (NB=–0.19 and corr up to 0.79, see Fig. 9.e). The
improvement due to rain gauge adjustment is less significant, particularly that of IR (see Fig. 9.f).

3). RESULTS AT X BAND
The global results obtained at X-band are represented in Fig. 10.

Figure 10. Results of each product without rain gauge adjustment (left hand side of panel) and with rain gauge adjustment (right hand) at X band.

The radar of Maurel is situated in a mountainous environment. The estimation of surface precipitation in such environment in rendered more difficult due to PBB and the fact that measurements are performed high above the ground. In addition, rain gauges tend to be placed down in the valleys, orographic enhancement effects not measurable by the radar should not be discarded in such conditions. This is the likely cause for the extremely low corr exhibited by the CONV method shown in Fig. 10.a). Part of the very large negative NB of the measurement can be attributed to radar misscalibration. In a
separate study, a radar-to-radar comparison in collocated pixels was performed between
the radar at Mont Maurel and that at Mont-Vial (Frasier et al. 2012). The study concluded
that the Mont Maurel radar was underestimating $Z_h$ by 2 dB with respect to the Mont-Vial
radar. Another cause for the underestimation of precipitation is wet-radome attenuation,
the effect of which is more significant at X-band that at a lower frequency. Again, the
adjustment using rain gauges significantly reduces NB although it fails to improve the
corr (see Fig. 10.b). As shown in Fig. 10.c) the attenuation correction of DBP1 results in
a reduction of roughly 0.2 in NB and an improvement of 0.1 in corr. The use of the rain
gauge adjustment improves the NB by roughly 0.2 respect to CONVA (see Fig. 10.d).
The best results by far are obtained by DBP2 (see Fig. 10.e). The use of $K_{dp}$, which is
insensitive to wet radome attenuation and PBB, largely reduces NB and it significantly
increases corr. The rain gauge adjustment further reduces NB (see Fig. 10.f). The NB
obtained by DBP2Adj is comparable to that obtained at the other frequency bands.

7. Conclusions

This paper has presented the situation regarding dual-polarization in France. After 8 years
of operations, the demonstration has been made that polarimetry brings clear added value
to all products provided that the quality of raw variables is accurately monitored. The use
of $K_{DP}$ in rainfall estimation is very valuable as this parameter is immune to partial beam
blocking, attenuation, calibration, … A significant improvement of high rain rates
estimation is obtained. The benefits increase with increasing radar frequency. Polarimetry
has become the new standard for operational radars in France.
References


