EVALUATION OF DUAL-POLARISATION TECHNOLOGY AT C-BAND FOR OPERATIONAL WEATHER RADAR NETWORK

OPERA 2
Work Packages 1.4 and 1.5
Deliverable b

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Release: Final version
Date: 12/12/06
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1. Motivations

In the frame of this OPERA2 work package, a questionnaire was sent to all OPERA delegates in order to draw information about the current status of dual-polarization within European countries. This questionnaire revealed that several EU countries are currently introducing the technology in their national radar network including Austria, France, Germany, Greece, Hungary, Italy, Slovenia, Sweden, and the United Kingdom. Not surprisingly, National Meteorological Services’ (NMS) expectations of dual polarization radars are for improving Quantitative Precipitation Estimate (QPE) and hydrometeor classification, especially hail retrieval and rain/snow discrimination. However none of these NMS have yet performed an operational evaluation of polarimetric QPE algorithms or polarimetric hydrometeor classification schemes. The operational implementation of those algorithms requires a fair amount of ground work regarding parameters quality assessments and monitoring. Robust tools need to be developed to perform automated calibration procedures, attenuation correction, non-meteorological echo identification, and bright band detection. The potential deterioration to dual polarization parameters due to orography and low bright bands also needs to be understood.

The aim of this report work is to analyze the potential problems arising from the use of dual-polarization in an operational context. Dual-polarization is a technology that provides more (actually more than twice as many) parameters than conventional technology. It is clear to everybody that those parameters clearly contain very valuable information for many radar applications and products. However, those variables require rigorous and continuous quality control procedures. In this work, we report the design of a series of procedures that can help checking the quality of the raw dual-polarization variables. This document aims to address these issues by reporting experiences gained by Météo-France and the Met Office on their operational C-band dual polarization radar.

This report is divided as follows:

- Section 2 describes the design and operational constrains of both radars.
- In Section 3 we discuss the theoretical and practical limits with which the polarimetric parameters of both radars can be estimated; this section also describes quality checks that NMS should perform upon purchasing a polarimetric radar.
- Section 4 considers calibration procedures and presents automated solutions that may be implemented on an operational system.
- In Section 5 we investigate the performance of an automated attenuation correction scheme which makes use of a polarimetric parameter.
- Section 6 considers the polarimetric signature of non-meteorological echoes and presents a technique based on fuzzy logic which proves to be very powerful.
- Section 7 considers the polarimetric signature of the bright-band which may be used to identify the transition from liquid phase hydrometeor to ice and snow.
- And finally, we present in Section 8 a work carried out by MeteoSwiss on assessing the effect of partial beam shielding on polarimetric parameters.
2. **Operating Characteristics of Trappes and Thurnham radar**

The radars used to carry the studies reported in this document are both equipped with linear polarization capabilities transmitting $45^\circ$ polarized waves and receiving waves at both Horizontal (H) and Vertical (V) polarization separately through two channels. Table 2.1 gives a description of the specification of both radars. The main difference in the designs of these two radars lies in the location of the receiver: The Trappes radar has its receiver conventionally located in the control room whereas the Thurnham radar has its receiver mounted at the back of the antenna. The latter configuration is designed to reduce waveguide losses and to eliminate rotating joints in the received path which may cause variations in the dual polarization parameters and calibration drifts.

<table>
<thead>
<tr>
<th>Name</th>
<th>Trappes Radar</th>
<th>Thurnham Radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>SW of Paris</td>
<td>SE of England</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Gematronic</td>
<td>EEC</td>
</tr>
<tr>
<td>Operational since</td>
<td>Sep. 2004</td>
<td>Jul. 2006</td>
</tr>
<tr>
<td>Antenna Type</td>
<td>Centre-fed paraboloid</td>
<td>Centre-fed paraboloid</td>
</tr>
<tr>
<td>Antenna Diameter</td>
<td>3.7 m</td>
<td>4.3 m</td>
</tr>
<tr>
<td>Beam width (3dB)</td>
<td>$&lt; 1.1^\circ$</td>
<td>$&lt; 1.0^\circ$</td>
</tr>
<tr>
<td>Side lobe level within $\pm 5^\circ$</td>
<td>$&lt;-25$ dB</td>
<td>$&lt;-27$ dB</td>
</tr>
<tr>
<td>Side lobe level beyond $10^\circ$</td>
<td>$&lt;-40$ dB</td>
<td>$&lt;-39$ dB</td>
</tr>
<tr>
<td>Gain (H and V)</td>
<td>$&gt; 43.8$ dB</td>
<td>$&gt; 45.3$ dB</td>
</tr>
<tr>
<td>Max cross polar isolation</td>
<td>$&lt;-30$ dB</td>
<td>$&lt;-29$ dB</td>
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<td>Peak power</td>
<td>250 kW</td>
<td>250 kW</td>
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<td>Frequency</td>
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<td>5.640 GHz</td>
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<tr>
<td>Wavelength</td>
<td>5.31 cm</td>
<td>5.31 cm</td>
</tr>
<tr>
<td>Minimum detectable signal</td>
<td>$&lt;-112$ dBm</td>
<td>$&lt;-112$ dBm</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>$&gt; 95$ dB</td>
<td>$\sim 100$ dB</td>
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<td>Receiver location</td>
<td>Control room</td>
<td>Antenna pedestal</td>
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<tr>
<td>Processor Characteristics</td>
<td>CASTOR2</td>
<td>EDRP9 and EDGE</td>
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<tr>
<td>Pulse width</td>
<td>2 $\mu$s</td>
<td>2 $\mu$s and 0.4 $\mu$s</td>
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<tr>
<td>Range gate resolution</td>
<td>240m x 0.5$^\circ$</td>
<td>250m x 1.0$^\circ$</td>
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<tr>
<td>Antenna rotation rate</td>
<td>7.5$/s$ low elevation</td>
<td>12$/s$ low elevation</td>
</tr>
<tr>
<td></td>
<td>15$/s$ high elevation</td>
<td>18$/s$ high elevation</td>
</tr>
<tr>
<td>PRF</td>
<td>Staggered Triple-PRT:</td>
<td>Single PRF: 300 Hz</td>
</tr>
<tr>
<td></td>
<td>379/321/305 Hz</td>
<td>Dual-PRF: 850/1180Hz</td>
</tr>
</tbody>
</table>

Table 2.1: Characteristics of Météo-France’s and the UK Met Office’s C-band dual-polarization radar

Table 2.2 defined the polarimetric parameters. Both radars have the capability to measure the reflectivity ($Z_H$ or $Z_V$), the differential reflectivity ($Z_{DR}$), the phase ($\Phi_{DP}$) and the amplitude of the cross-correlation coefficient at zero lag ($\rho_{HV}(0)$), the linear depolarization ratio (LDR), and the Doppler moments.
Reflectivity in dBZ

\[ Z_H = 10 \log_{10} \left( \frac{\langle |S_{HH}|^2 \rangle}{\langle |S_{VV}|^2 \rangle} \right) \]

Differential Reflectivity in dB

\[ ZDR = 10 \log_{10} \left( \frac{\langle |S_{HH}|^2 \rangle}{\langle |S_{VV}|^2 \rangle} \right) \]

Differential phase shift in degree

\[ \Phi_{DP} = \arg \left( \frac{\langle S_{HH}^* S_{VV} \rangle}{\sqrt{\langle |S_{HH}|^2 \rangle \langle |S_{VV}|^2 \rangle}} \right) \]

Co-polar Correlation coefficient

\[ \rho_{HV}(0) = \left| \frac{\langle S_{HH}^* S_{VV} \rangle}{\sqrt{\langle |S_{HH}|^2 \rangle \langle |S_{VV}|^2 \rangle}} \right| \]

Linear Depolarization Ratio in dB

\[ LDR = 10 \log_{10} \left( \frac{\langle |S_{HV}|^2 \rangle}{\langle |S_{HH}|^2 \rangle} \right) \]

where \( S_{HH} \) (\( S_{VV} \)) is the co-polar horizontal (vertical) component of the backscatter amplitude and \( S_{HV} \) is the cross-polar return at vertical polarization for a horizontal polarized transmission. The inner brackets indicate averaging across each \( i^{th} \) independent sample in each range gate.

Table 2.2: Dual polarization parameters measured by Météo-France and the UK Met Office.

The procurement of LDR makes the transmission strategy and the computation cost more complex. For instance, the scan strategy of the Thurnham radar alternates LDR scans (H transmission only) with regular dual-polarisation scans (H and V transmission). From day 1, both radars were required to perform as part of an automated operational network, and to meet the requirements of the end users in terms of quality of surface rainfall rate, timeless and reliability. The data had to fit into the existing suite of composite and single site radar products at a similar quality than existing radar on the UK or the French network. These key points played a major role in designing a scan strategy that would meet the NMS’s end users needs whilst providing enough flexibility to develop new algorithms using the added information supplied by dual-polarization parameters. Common to both scan strategies are the length of each scan cycles (5-mins), and the use of 2 to 3 types of cycles to incorporate slow low elevation angle scans for rainfall rate measurements, fast higher elevations scans for VAD wind measurements, and a scan at 90° for \( Z_{DR} \) calibrations (see Table 2.3). Data collected at vertical incidence have proven to be quite useful for \( Z_{DR} \) and \( \rho_{HV}(0) \) data quality purposes. The Trappes radar operates a staggered PRT scheme developed for retrieving and dealiasing Doppler velocities (Tabary et al. 2005). The Thurnham radar operates a standard single PRF at 300 Hz at low elevation angle for rainfall rate measurements, and a dual PRF at 850/1180 Hz at high elevation angle for Doppler wind measurements. Given the operational constrains of both radars, the total number of samples at a
given range gate is 23 for Trappes, and 25 for Thurnham (for reflectivity measurement i.e. operating in long pulse mode).

Thurnham radar alternates 2 cycle everything 10 minutes:
- Cycle 1 comprises 6 rainfall rate measurement scans in simultaneous H and V transmit and receive, followed by 4 fast Doppler measurement scans.
- Cycle 2 comprises 6 rainfall rate measurement scans in simultaneous H and V transmit and receive, followed by 2 LDR measurement scans, and finishing with 1 vertically pointing ZDR calibration scan.

Trappes radar alternates 3 cycle everything 15 minutes comprised of 6 scans. Every cycle comprise scans at 0.4, 0.8, 1.5 and 2.5 degree. The remaining 2 scans are filled by vertically pointing scans for ZDR calibration (once every 15 mins), or by scans at higher elevation i.e. between 3.6 to 9.0 degree.

Table 2.3: Scan strategy for the Thurham (top) and Trappes radar (bottom).
3. System Noise Analysis

3.1. Overall Measurement Precision

The estimate of measurement error of polarimetric parameters gives an assessment of the quality of the radar hardware and data acquisition system. It is essential to perform such analysis upon purchasing new radars particularly for $Z_{DR}$ and $\Phi_{DP}$ as the accuracy of the measurement of these two parameters defines the level of improvement in polarimetric QPE. This analysis can highlight potential problems with the radar system and these should be raised with the manufacturer as soon as possible. The theoretical value of the error of each parameter can be derived according to the specific operating characteristics of the radar and express as a function of spectrum width, as derived by Bringi and Chandrasekar (2001). Aside from limitations due to the microphysical properties of the observed sample volume, the measurement errors of $Z_{DR}$ and $\Phi_{DP}$ are limited by hardware imperfections which result in the degradation of the correlation coefficient between the H and V time-series. Thus the first “health” check that NMS should carry out is to estimate the peak value of $\rho_{HV}(0)$ in rain.

In simultaneous transmit and receive mode $\rho_{HV}(0)$ from rain is at least 0.98 (Illingworth, 2003; Zrnic et al, 2005). More recent reports from operational C-band dual-polarization radars i.e. the Trappes radar near Paris (Gourley et al, 2006) and the King City radar near Toronto, have reported $\rho_{HV}(0)$ peak values in rain better than 0.990. However observations from the Thurnham radar (Figure 3.1), have recorded $\rho_{HV}(0)$ peak values in rain of 0.975 at best. This poor performance of the Thurnham radar most probably indicate problems either with the digital receiver (caused by differential non-linearity between the two A/D), or with the antenna i.e. miss-match between the H and V beam pattern. These two theories are currently under investigations.

![Figure 3.1: Distribution of the co-polar correlation coefficient for samples collected in rain by the Thurnham radar. The peak value measured is 0.975 with less than 5% of observation greater than 0.990.](image-url)
Using the observed peak value of $\rho_{HV}(0)$, the theoretical measurement errors for $Z_{DR}$ and $\Phi_{DP}$ may be estimated as derived by Bringi and Chandrasekar (2001). The results for the Trappes and Thurnham radars are shown in Figure 3.2.

![Figure 3.2: Theoretical measurement errors of (left) Differential reflectivity, and (right) Differential phase, versus Doppler spectrum width (m/s). Calculations assume $\rho_{HV}(0)$ peak value in rain of 0.99 for Trappes and 0.975 for Thurnham.](image)

The observed measurement errors of $Z_{DR}$ and $\Phi_{DP}$ were evaluated in light stratiform rain, and compared to theoretical expectations. An altitude threshold was imposed on to restrict sampling below the bright-band i.e. sampling only hydrometeor in liquid phase. The dataset was limited to data associated with $\Phi_{DP}$ less than 10° to avoid bias caused by attenuation. Nine-gate windows along a radial were used to compute the standard deviation. Larger windows would increase the precision of the standard deviation but will also increase the value of the standard deviation due to natural variability and/or due to azimuth variation caused by radome interference (see Section 4.3). The standard deviations were computed for non-normalized spectrum widths of 1 m/s and for $\rho_{HV}(0)$ values of 0.99 for Trappes and 0.975 for Thurnham. Comparisons between theoretical and observed values are shown in Table 3.1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Radar</th>
<th>Standard Deviation</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Theoretical</td>
</tr>
<tr>
<td>$Z_{DR}$</td>
<td>Trappes</td>
<td>$\pm 0.26$ dB</td>
</tr>
<tr>
<td>$Z_{DR}$</td>
<td>Thurnham</td>
<td>$\pm 0.43$ dB</td>
</tr>
<tr>
<td>$\Phi_{DP}$</td>
<td>Trappes</td>
<td>$\pm 1.75^\circ$</td>
</tr>
<tr>
<td>$\Phi_{DP}$</td>
<td>Thurnham</td>
<td>$\pm 3.0^\circ$</td>
</tr>
</tbody>
</table>

Table 3.1: Comparison between theoretical and observed precision errors for differential reflectivity and differential phase shift, for $\rho_{HV}(0)$ values of 0.99 (Trappes) and 0.975 (Thurnham) and a Doppler spectrum width of 1 m/s.

Observational values of the standard deviation of all parameters fall within theoretical expectations. The precision on $Z_{DR}$ required for accurate estimates of rainfall rate is around 0.2
dB (Illingworth, 2003), which is expected to be reached for $\rho_{HV}(0)$ values of at least 0.99. At $\rho_{HV}(0)$ values below 0.99, further averaging of the data will be required to increase the accuracy of the parameters.

From the analysis we can conclude that the Trappes radar is performing as well as expected with a very high matching of the H and V beam pattern. On the other hand there are concerns that this might not be the case for the Thurnham radar; the issue is currently under investigation as this will greatly affect the level of performance of QPE algorithms and precipitation type classification schemes.

3.2. Correcting for System noise

There are several sources of noise both internal and external to a radar system (Bringi and Chandrasekar 2001). Receiver noise in both channels may be measured internally. However, it is the contribution of both external and internal noise that biases measurements of polarimetric variables. Gourley et al. (2006b) propose an approach to estimate the effective noise using actual measurements in rain at vertical incidence. While the powers of noise at both horizontal and vertical polarizations may not be known precisely, there exists a mathematical basis for including the ratios of horizontal to vertical noise powers into calculations of polarimetric variables (Liu et al. 1994), as shown by equations (3.1) and (3.2). Without this correction procedure, noise powers may induce biases in measurements of $Z_{DR}$ and $\rho_{HV}(0)$ at low signal-to-noise ratios (SNR).

$$Z_{dr}^m = \frac{1 + \text{snr}}{1 + \frac{\text{snr}}{\alpha Z_{dr}^{in}}}$$  \hspace{1cm} (3.1)

$$\rho_{hv}^m(0) = \frac{\rho_{hv}^{in}(0)}{\sqrt{(1 + \frac{1}{\text{snr}}) \times (1 + \frac{Z_{dr}^{in}}{\alpha \times \text{snr}})}}$$  \hspace{1cm} (3.2)

The signal to noise ratio and the differential reflectivity in this case are in linear units so “snr” and the subscript, “dr”, have been put in lower case. The superscripts “m” and “in” refer to the measured and intrinsic value, respectively. $\alpha$ represents a parameter used to describe the ratio of effective noise in the horizontal channel to that in the vertical channel.

The behavior of $Z_{dr}^m$ and $\rho_{HV}^m(0)$ (Figure 3.3) are evaluated using precipitation at vertical incidence for different values of SNR. These plots are created from data points that were measured at altitudes greater than 0.7 km to ensure that the data in the analysis are collected in the antenna’s far-field. Furthermore, non-meteorological backscatterers were removed from the dataset using procedures detailed in section 6. Figure 3.3 show that values of measured $Z_{DR}$ and $[1 - \rho_{HV}(0)]$ are increasing as SNR fall below 25 dB, which suggests that contributions from noise in the horizontal channel of the Trappes radar induce a small bias in the apparent $Z_{DR}$ values. These observation collected at vertical incidence are used to optimize the $\alpha$ parameter in
Equation (3.1) since the intrinsic $Z_{DR}$ is known to be 0 dB. The advantage of this approach is the utilization of measurements in rain where the combined effects of noise internal and external to the radar system are considered. The disadvantage is the scarcity of observations that are available at low SNR while the radar is pointing vertically, thus uncertainty exists in the estimate of $\alpha$. Nevertheless, this information allows us to solve an unknown constant, and then compute corrected values of polarimetric variables.

Figure 3.3: The normalized density of SNR (in dB) versus $Z_{DR}$ (top) and $\rho_{HV}(0)$ (bottom), for stratiform precipitation measured at vertical incidence using the Trappes radar. (Top diagram) The black line refers to the average measured $Z_{DR}$ while the dotted lines correspond to one standard deviation, blue refers to simulated $Z_{DR}$ with a –0.08 dB calibration error, and the red one corresponds to simulated $Z_{DR}$ with errors caused by noise and miscalibrated $Z_{DR}$. (Bottom diagram) The black line refers to the average measured $\rho_{HV}(0)$, blue refers to simulated $\rho_{HV}(0)$ with a –0.08 dB calibration error in $Z_{DR}$, and the red one corresponds to simulated $\rho_{HV}(0)$ with errors caused by noise and miscalibrated $Z_{DR}$. 
4. Monitoring and Calibration

4.1. Calibration of the Horizontal reflectivity

Dual polarization technology provides a novel approach to calibrate Z, which was first presented by Goddard et al. (1994), based on the well-defined behaviour of the specific differential phase shift ($K_{DP}$) scaled by Z versus $Z_{DR}$. This relationship has been shown to be virtually independent of variations in drop size distributions (DSDs). This technique compute from measured values of Z and $Z_{DR}$ using a raindrop shape models e.g. Pruppacher and Pitter (1971), Beard and Chuang (1987), Goddard et al. (1995). The estimated $K_{DP}$ is then integrated in the radial direction to compute a value of $\Phi_{DP}$. Differences between measured and computed $\Phi_{DP}$ are attributed to miscalibration in Z and provide a basis for correcting it. Gourley and Illingworth (2005) examined this concept using the Trappes radar. Their recommendations are as follows:

- $Z_{DR}$ should be well calibrated and should be free of azimuth dependency (see section 4.2).
- $\Phi_{DP}$ should be corrected for initial system offset and should be free of azimuth dependency (see section 4.3).
- $\Phi_{DP}$ should be a sufficiently large to be measured with reasonable accuracy but not so large as to indicate significant attenuation is taking place. At C-band, it is recommended to limit the analysis to $\Phi_{DP}$ values lower than 10°.
- Raindrop shape models are valid for raindrops alone. Therefore care should be exercised to ensure that the data is free of fixed target, hailstones, and melting hydrometeors.
- Many rays have to be processed to make the estimation statistically significant. The selection of the eligible rays turned out to be of prime importance.

Based on their study, Gourley and Illingworth (2005) concluded that the Trappes radar was miscalibrated by -1dB, and reported excellent results between observed and derived $\Phi_{DP}$ values using either the Beard or Goddard model. Follow on work by Gourley et al. (2006a) examined the sensitivity of calibration to a wider range of raindrops shape models, and reported that the Brandes et al. (2002) model provided the most consistent results. More work is still required to make the calibration estimation fully automatic.

4.2. Calibration and monitoring of the Differential Reflectivity

4.2.1. From hydrometeor measurements at vertical incidence:-

At vertical incidence, raindrops should appear spherical hence $Z_{DR}$ should be 0dB. Thus, measurements carried out at vertical incidence in rain may be used to examine the absolute calibration of $Z_{DR}$. While mean canting of raindrops or an imprecise pointing angle lead to variable $Z_{DR}$ measurements, an average across all azimuth should be 0 dB; any deviation from 0 can be attributed to slight hardware differences in the H and V channels and should be removed from the raw $Z_{DR}$ measurements.
Several hours of stratiform rainfall event on 17 Dec 2004 (Trappes) and 26 May 2006 (Thurnham) are used for this report to illustrate the evaluation of the calibration errors in $Z_{DR}$. A total of 24 and 36 scans (for Trappes and Thurnham, respectively) comprise the dataset. Normalized density plots were created from each data points free of non-weather echoes (see section 6), and measured at altitudes beyond the antenna’s far-field (e.g., altitudes greater than 0.7 km). Figure 4.1 indicates that $Z_{DR}$ has a negative bias for both Thurnham and Trappes. Thus, the calibration error in $Z_{DR}$ as computed by precipitation sampling at vertical incidence is $-0.08 \pm 0.9$ dB and $-0.97 \pm 0.95$ dB for Trappes and Thurnham, respectively.

Figure 4.1: $Z_{DR}$ calibration diagrams derived from measurements at vertical incidence, collected by (a) Trappes radar, and (b) Thurnham radar.
At Thurnham, the variation of mean $Z_{DR}$ with the azimuth follows a sinusoidal trend with wavelength of 180˚ and an amplitude of 0.12 dB (Figure 4.1b). Thurnham radar’s receiver is located in the radome at the back of the antenna; this arrangement removes the need to use rotating joints on the receive path, and therefore the sinusoidal interference observed in Figure 4.3b can not be attributed to rotating joints. Instead, obstruction light fittings located inside the radome (shown in Figure 4.2) are believed to be causing this sinusoidal variation in $Z_{DR}$ measurements. However, this interference is not believed to have an effect on low elevation measurements, and cancels out for the estimates of $Z_{DR}$ offset by averaging $Z_{DR}$ data across azimuth.

![Figure 4.2: View of the obstruction light fittings inside the Thurnham’s radome.](image)

The zero offset of the $Z_{DR}$ measurements collected at the Trappes has been monitored regularly since September 2004. Figure 4.3 shows a snapshot of the temporal variation of $Z_{DR}$ offset between January and August 2005. During the first period, the offset was fairly stable at -0.08 dB. The offset started exhibit sharp variation in February 2005 which became more frequent from April 2005. Damages to the rotating joints were soon discovered to be the cause for these variations; they were replaced in July resulting in the return of a stable $Z_{DR}$ offset at -0.08 dB.

![Figure 4.3: Variation of $Z_{DR}$ offset of the Trappes radar between January and August 2005.](image)
In an operational environment it is very important to continuously monitor the $Z_{DR}$ offset as it may serve to readily highlight hardware problems that might otherwise take month to detect. It is also very important because $Z_{DR}$ measurements should be calibrated to 0.1 dB to be used in QPE algorithms. Therefore we recommend that NMS include a vertical scan (at least one every 15 mins) in their scan strategy. However for some radar site vertical scan might not be possible due to hardware or location constrains so for those sites we would recommend to perform $Z_{DR}$ offset calibration using measurements from solar radiation.

4.2.2. From measurements of solar radiation:-

Solar radiation has equal power at both vertical and horizontal polarizations, thus the $Z_{DR}$ is 0 dB regardless of elevation angle. Data collected near sunrise can be analyzed to detect the presence of solar radiation along each radial. This analysis was performed on 16 tilts of data per volume scan (the 9° and 90° data are excluded) from 17 Dec. 2004 to 11 Jan 2005 (using Trappes radar). Solar radiation along a radial, or a “sun spike”, was automatically found if there are at least 500 gates that meet the following criteria:

- Solar radiation typically produces reflectivity measurements comprised between –10 and 20 dBZ, thus this threshold was imposed.
- According to theory, $\rho_{HV}(0)$ should be 0 in a sun spike. This was not always observed, yet a threshold of $\rho_{HV}(0)$ less than 0.5 may be sufficient to distinguish solar radiation from hydrometeors.

Using data collected from the Trappes radar, a probability distribution was computed from the sun spike dataset and is shown in Figure 4.4. The curve is well approximated by a Gaussian with a mean value shifted toward negative $Z_{DR}$ values i.e. -0.2 ± 1.4 dB. Both $Z_{DR}$ calibration methods (i.e. measurements at vertical incidences and measurements of solar radiation) are in agreement for the Trappes radar.

![Figure 4.4: $Z_{DR}$ calibration diagrams derived from solar radiation collected by the Trappes radar](image)

Measurements from hydrometeors at vertical incidence are capable of testing the combined effects of reception and transmission on the absolute calibration of $Z_{DR}$. The “sun spike” analysis tests only the reception component of the radar, and results have more
uncertainty given the larger standard deviation. It is thus preferable to use precipitation measurements at vertical incidence to calibrate $Z_{DR}$ if this option is available with the radar system. Otherwise, calibration using solar radiation may be sufficient.

4.3. **Azimuth dependencies of $Z_{DR}$ measurements**

An experiment was carried out to investigate the possibility of variation of $Z_{DR}$ measurements with the azimuth. We are interesting in highlighting interference caused by man-made structures or vegetations in the close proximity of the radar, resulting in repeatable variation in $Z_{DR}$ measurements as a function of azimuth. “Natural” causes of azimuth variation of $Z_{DR}$ measurements (e.g. climatological variability, attenuation produced by heavy precipitation, and enhancement induced by the bright-band) should be excluded from this experiment by making a few restrictions to the dataset. To conduct this analysis, the data sample was therefore refined to $Z_{DR}$ measurements from light rain by imposing an altitude threshold in order to limit the data sample to rain measurements below the melting layer. Limiting the data set to values of $\Phi_{DP}$ less than 10° reduces errors due to attenuation. An additional threshold of SNR greater than 25 dB was also enforced in order to mitigate biases in $Z_{DR}$ and $\rho_{HV}(0)$ at low SNR. Finally the data was cleared from pixels likely to be contaminated by non-weather targets using techniques described in Section 6. Figure 4.5 shows the variation of average $Z_{DR}$ with the azimuth derived from several stratiform events for the Trappes and Thurnham radars. In both cases, the azimuth variations of $Z_{DR}$ follow a clear sinusoidal trend of 0.1-0.2 dB amplitude and a wavelength of 60° at Trappes and 45° at Thurnham.

![Figure 4.5: Variation of mean differential reflectivity (corrected for zero offset) with the azimuth for data collected at low elevations by the Thurnham radar (top – using a dataset of 9 stratiform events) and the Trappes radar (bottom – using a dataset of 15 stratiform events).](image)

These trends most likely result from power losses at azimuths near the connecting joints radome panels. Both radars have an orange peel arrangement type radome (Figure 4.6), however they are slightly different: The Trappes’ radome is composed of 6 panels fixed together with glued; the Thurnham’s radome comprises of 8 panels for the lower 2/3 of the radome and 4
panels on top which are assembled with stainless steel bolts. Result for Thurnham shown also suggests the data is affected by more than one source of interference. FFT analysis reveals that the variation of $Z_{DR}$ with azimuth is composed of two sinusoidal trends: one with a wavelength of $45^\circ$ and another with a wavelength of $180^\circ$.

Figure 4.6: View of the Thurnham radar’s radome (left), and view of the Trappes radar’s radome (right).

Further work is underway to characterize this interference and derive a formula to correct the data. However at this stage, it is not known whether this is feasible and whether this solution will be sufficient to reach the required accuracy for QPE algorithms. An alternative (more costly) solution will be to replace the radome. Modeling experiments carried out by Manz et al (1998), suggests that quasi-random panel radomes are the better suited for dual polarization radars although there are at present no reported practical observation to support this claim.

4.4. **Calibration and monitoring of the System offset of Differential Phase**

A nonzero initial differential phase ($\Phi_0$) may occur due to very slight differences between the horizontal and vertical waveguides. A slight offset in distances can result in either a positive or negative phase difference. As shown in section 4.1, absolute values of $\Phi_{DP}$ may be required to calibrate $Z_h$, thus it is essential that $\Phi_0$ is defined and used to correct $\Phi_{DP}$. Possible offsets in initial differential phase measurements can be determined using several restrictions to the dataset:

- Upper and lower thresholds of $Z_h$ (30dBZ and 20dBZ) should be imposed in order to excluding positive differential phase shifts caused by moderate to heavy rain, and measurements taken at low SNR.
- Data should be measured at a distance greater than 5 km from the radar but within 50 km, in order to excluded data collected in heavily cluttered areas, and measurements taken at low SNR.
- The location of the bright band should be defined (manually by examining $\rho_{HV}(0)$ measurements, or by using model data). Only data collected below the bright band should be included in the analyses.
A threshold on $p_{HV}(0)$ should also be imposed in order to refine the dataset to measurements that are likely observed in precipitation.

The remaining $\Phi_{DP}$ values should be run through a simple dealiasing algorithm i.e. subtract 360° from all raw $\Phi_{DP}$ measurements greater than 270°.

Figure 4.7 shows examples of the behavior of $\Phi_o$ as a function of azimuth angle for the Trappes and Thurnham radars, where the mean $\Phi_o$ is approximately - 6° at Trappes and -38° at Thurnham. If the system offset of differential phase shift were constant with azimuth, then $\Phi_{DP}$ measurements could be adjusted by simply subtracting out the mean $\Phi_o$ value. However, closer inspection of the estimated $\Phi_o$ trends reveals that they follow a sinusoid.

At Trappes the sinusoidal trend has a wavelength of 360° and an amplitude of approximately 2.25°. This sine wave appears to recur with a similar behavior for all cases analyzed. The wavelength and repeatability from case-to-case suggest that to the waveguide rotary joint are the cause for the $\Phi_{DP}$ dependence on azimuth. Gourley et al. (2006b) developed and implemented an empirical correction procedure to account for this artifact: First, a sine wave is manually fit to the observed mean $\Phi_o$ curves shown in Figure 4.7. This sine wave is then shifted 180° in azimuth and then added back to $\Phi_{DP}$ measurements. In addition, a factor of 6° is included in the correction formula to account for the mean bias in $\Phi_{DP}$ as follows:

$$\Phi_{DP}^m = 2.25\sin(\theta + 230) + \Phi_{DP}^m + 6$$
where all values are in degrees and the superscripts “in” and “m” refer to intrinsic and measured values. The correction method is shown to adequately account for the sinusoidal behavior and negative bias present in the original Φ₀ measurements. The resulting mean Φ₀ values now have very little bias and are no longer dependent on azimuth.

At Thurnham the sinusoidal trend is more ambiguous: FFT analysis suggests that Thurnham differential phase measurements are affected in two ways: one with a wavelength of 60° and the other with a wavelength of 180°. Unlike Trappes radar, Thurnham does not have rotating joints on the receive path which could have explained the interference with an 180° wavelength. At this stage, the causes of these trends are not known, and work is underway to characterize this interference and derive a formula to correct the data.

The zero offset of the Φ_PD of the Trappes radar has been monitored regularly since September 2004, and has shown to be very stable at -6° (Figure 4.8).

![Figure 4.8: Variation of Φ_PD offset of the Trappes radar between January and August 2005.](image)
5. Attenuation Correction

5.1. Background and Methodology

Bringi and Chandrasekar (2001) provide an excellent summary of methods to correct for attenuation of $Z_H$ and $Z_{DR}$ using the phase difference between horizontally and vertically polarized returns ($\Phi_{DP}$). As raindrops grow they become more oblate leading to positive values of $Z_{DR}$, and the slower velocity of the H wave relative to V leads to a value of $\Phi_{DP}$ which increases with range in a rainfall medium. Figure 5.1 is an excellent illustration of the potential of $\Phi_{DP}$ to diagnose attenuation on $Z_H$ and $Z_{DR}$. It shows PPIs of $\rho_{HV}(0)$, $\Phi_{DP}$, $Z_{DR}$ and $Z_H$ during a convective weather event. The attenuation of $Z_{DR}$ and $Z_H$ is obvious in the southwest of the domain. $\Phi_{DP}$ reaches a maximum of 100$^\circ$ in the attenuated sector.

![Figure 5.1: 512×512 km PPIs of $\rho_{HV}$, $\Phi_{DP}$, $Z_{DR}$ and $Z_H$ during a convective weather event a resolution of 1km$^2$.](image)

Scattering simulations assuming gamma functions for rain drop size distributions suggests that at C-bands the attenuation ($A_H$, in dB) and the differential attenuation ($A_{HV}$, in dB/km) are nearly linearly related to $K_{DP}$ (the gradient of $\Phi_{DP}$ with range in deg/km) by coefficients $a$ and $b$, respectively (Bringi et al., 1990). These coefficients can vary due to changes in temperature and DSD characteristics. Ryzhkov and Zrnic (1995) produced scatter plots of $\Phi_{DP}$ versus $Z_H$ and $\Phi_{DP}$ versus $Z_{DR}$ using a large data set; the slope of the fitted lines...
yields values of $a$ and $b$ larger than Bringi et al. (1990), which is attributed to additional attenuation due to Mie scattering (Smyth and Illingworth 1998). Carey et al. (2000) adapted the technique of Ryzhkov and Zrnic (1995) by identifying rays with Mie scattering effects (equi-volumetric median diameter drops > 2.5 mm). This was done by looking for large $Z_{DR}$ values along the ray ($Z_{DR} > 2.5$-3 dB at C-band). Larger coefficients (two times larger for $a$ and four times larger for $b$) were applied to these rays if they had large differential phase, dips in the copolar cross-correlation coefficient at zero time lag ($\rho_{HV}(0)$), and high values of $K_{DP}$. The degree of scatter surrounding the least squares linear regressions is suggestive of significant uncertainty in the derived coefficients.

Smyth and Illingworth (1998) proposed a method based on constraining values of $Z_{DR}$ behind intense convective cells where the intrinsic $Z_{DR}$ is believed to be 0 dB, representing spherical droplets. Observations of negative $Z_{DR}$ are used to correct for horizontal and differential attenuation effects; the total differential attenuation is then redistributed to gates along the radial with $K_{DP}$ greater than 1 deg/km, yielding an estimate of $A_{HV}$. A linear relationship is then assumed between $A_{HV}$ and $A_{H}$ based on scattering simulations thus providing for a correction to values of $Z_{H}$ and $Z_{DR}$. This method offers the advantage of being applicable on a ray-by-ray basis. However, the constraint of an intrinsic $Z_{DR}$ of 0 dB in drizzle regions, for which the method is based, is difficult to automatically identify using other polarimetric parameters.

The ZPHI algorithm (Testud et al. 2000) is similar in design to the original technique of Hitschfeld and Bordan (1954) with the additional constraint of estimating the reference attenuation. The $\Phi_{DP}$ constraint leads to numerical stability, which is the main failing with the original technique. The ZPHI algorithm may yield inaccurate results due to deviations from the assumed raindrop size-shape model and in situations where the observed $\Phi_{DP}$ is small compared to system noise levels. Also, $Z_{H}$ values become biased along with the estimated $A_{H}$ if measurements from hail or mixed-phase hydrometeors are included in the calculations. This method has been modified by adding a combined $\Phi_{DP}$-$Z_{DR}$ constraint as described in Bringi and Chandrasekar (2001).

5.2. Verification of the linearity of PIA as a function of $\Phi_{DP}$

In an operational context, the argument of simplicity is very important. This is the reason why a basic correction Path Integrated Attenuation (PIA = $a \times \Phi_{DP}$) has been tested. To start with, the linearity of the PIA as a function of $\Phi_{DP}$ had to be verified. Gourley et al. (2006c) proposed a method to empirically estimate the PIA. This method relies on the fact that the azimuths of attenuated sectors (the “searchlights”) are changing rapidly with time, as attenuating convective cells pass in the radar domain. Another assumption of this method is that on average, the main source of variation between two successive but synchronized (i.e. corrected for advection) radar images is attenuation. In convective situation, there may be growths and decays of the cells, but on average those effects should cancel out. Figure 5.2 summarizes the method. Under those assumptions and with some linear algebra, it is possible to derive an empirical curve for PIA as a function of $\Phi_{DP}$.
Météo-France ran this analysis on 7 severe convective cases. Figure 5.3 shows the 7 corresponding curves which are found to lie within the theoretical bounds reported in literature. Furthermore, all curves are monotonic functions of $\Phi_{DP}$, which confirms the fact that $\Phi_{DP}$ is a very good indicator of attenuation. In addition, all curves are close to linear, which confirms the relevance of a simple linear $\text{PIA} = a \times \Phi_{DP}$ correction.

Figure 5.3: Retrieved curves (in black) of a) $\Phi_{DP}$ vs. PIA and b) $\Phi_{DP}$ vs. path-integrated differential attenuation, for seven cases of intense convection. The slopes of the gray lines correspond to the minimum and maximum correction coefficients published in simulation-based and empirical studies.
The variability among the curves could be attributed to temperature and DSD. To test this hypothesis, the results were segregated according to temperature and Z_{DR}. However surprisingly, segregation with temperature did not appear very conclusive. This may be due to the difficulty arising from computing the relevant temperature, which is the wet-bulb temperature of attenuating cells. The radiosonde data that were used might have been too coarse, from a spatial and temporal point of view to perform segregation correctly. On the other hand, the segregation with Z_{DR} and in particular with the occurrence of large (greater than 3 dB) Z_{DR} along the ray gave a much clearer result, as shown in Figure 5.4. The presence of large Z_{DR} (drops) tends to increase the $a$ and $b$ coefficients. There is a factor of 3 between the maximum and the minimum coefficients.

![Figure 5.4](image)

**Figure 5.4:** $a$ (stars) and $b$ (pluses) coefficients retrieved empirically stratified according to the occurrence of large Z_{DR}.

Reflectivity data were corrected using the coefficients retrieved by the method and compared to the reflectivity measurements of the neighboring radars. Care was taken to choose events were neighboring the reflectivity data from radars were not attenuated, and that there was no calibration bias between the 2 radars. Figure 5.5 shows the results of the radar – radar comparison (i.e. between the Trappes and Abbeville radars).

![Figure 5.5](image)

**Figure 5.5:** Trappes – Abbeville comparison before (light grey) and after (black) the Trappes radar data were corrected for attenuation. The Abbeville radar is located 150 km north of Trappes.

5.3. *Analysis of the ZPHI attenuation correction procedure*
The ZPHI algorithm was implemented in real-time on the Météo-France system, and ran all through 2005. More than 25 significant situations we selected to perform its evaluation against rain gauges. The ability of ZPHI to correct for attenuation was specifically evaluated. The attenuation correction essentially relies in a linear relationship between specific attenuation and specific differential phase. The coefficients of the linear relationship are temperature-dependent and very slightly N0* dependent. Figure 5.6 shows a radar – raingauge scatterplot to illustrates the ability of a simple $\text{PIA} = a \times \Phi_{DP}$ relationship, to correct for attenuation. Hourly accumulations of strong attenuation cases were considered to produce Figure 5.6. The normalized bias goes from 31% underestimation to 13% overestimation.

![Radar – raingauge scatterplot](image)

**Figure 5.6:** Radar – raingauge scatterplot in attenuation conditions, (left) without attenuation correction, and (right) with attenuation correction performed by ZPHI.

Figure 5.7 further illustrates the improvement in gradually increasing attenuation conditions. Hourly accumulations were stratified according to the severity of attenuation, given by the mean $\Phi_{DP}$ over the hour.

![Normalized bias](image)

**Figure 5.7:** Normalized bias with (POL1) and without (CONV) attenuation correction for different class of attenuation.
Figure 5.7 is very clear: without attenuation correction, the normalized bias decreases very rapidly in severe attenuation conditions. This is a major problem because it is especially in such critical cases that the radar data have to be very accurate.

5.4. **Recommendations and operational considerations**

In the previous paragraph, we have shown that it is quite reasonable to attempt to identify and correct attenuation and differential attenuation with the differential phase $\Phi_{DP}$. Such corrections are important for quantitative precipitation estimation and for particle-type identification. The use of the absolute value of $\Phi_{DP}$ to correct for attenuation has many advantages from an operational point of view:

- The correction for attenuation and differential attenuation is straightforward and computationally inexpensive. The correction can be done on a gate-by-gate basis. It is not necessary to determine the first and last valid gate and apply the correction procedure to the selected segment. The correction can even be done in Cartesian coordinates.
- Because of ground-clutter, polarimetric data are usually not available at close ranges from the radar. At low elevation angle, it is not rare that the first valid gate is located at around 10 km from the radar. Yet heavy rain may take place in that area. If there is indeed attenuation, then $\Phi_{DP}$, being a propagation variable, will normally trace it and allow correction of the PIA that occurred in the vicinity of the radar. A particular case of that is wet radome attenuation. We have noticed a clear signal on $\Phi_{DP}$ in such cases (not shown here).

The use of $\Phi_{DP}$ however requires to:

- Carefully monitor the system differential offset ($\Phi_0$);
- Correct $\Phi_{DP}$ for all the possible variations along the azimuth (see section 4.4).
- Implement a basic unfolding procedure (see Section 4.4).
- Calibrate for the system differential phase. This offset was found to be quite stable over time in the Trappes radar.

It is not really necessary to smooth $\Phi_{DP}$ to use it for attenuation correction. The noise on $\Phi_{DP}$ is typically 2 degrees (see section 3.1), which, given the $a$ and $b$ coefficients of the linear relationships, does not significantly impact the PIA and differential PIA. An experiment is currently underway by Vulpiani et al. (2006) to compare several attenuation correction procedures in order to define the best operational candidate. Special emphasis is laid on the robustness and simplicity of the method and the ability to account in real-time for the temperature and DSD dependencies of the ‘a’ and ‘b’ coefficients.

We propose the following 3 options to implement an attenuation correction technique into an automated processing system:

(OPTION 1) Use unfolded, bias-corrected $\Phi_{DP}$ to correct $Z_H$ and $Z_{DR}$ for attenuation with a static linear relationship $\text{PIA} = a \times \Phi_{DP}$ and differential $\text{PIA} = b \times \Phi_{DP}$.
(OPTION 2)  Apply (OPTION 1) and use temperature information (e.g. from surface stations, radiosondes, or from model forecasts) in the $\text{PIA} = f(\Phi_{DP})$ relationship. The dependency of the relationship with respect to temperature is well known from a theoretical point of view but it may practically be difficult to get the adequate temperature.

(OPTION 3)  Apply (OPTION 2) and use some statistics on $Z_{DR}$ along the ray to improve the $\text{PIA} = f(\Phi_{DP})$ relationship.

Météo-France currently applies a (OPTION 1) on the Trappes data.
6. Non-meteorological echo identification

6.1. Background

The availability of dual-polarization variables is a very good opportunity to improve the non-meteorological echo identification and removal. Using conventional radars ground-clutter for instance can be identified with statistical maps or, in a dynamical fashion, with the Doppler spectrum or, as it is done at Météo France and at the Met Office, with the pulse-to-pulse reflectivity fluctuation (Sugier et al. 2002). Sunrise and sunset signatures can be identified from their very particular appearance and from the fact that they occur at predictable times. Sea-clutter may be removed by considering the vertical gradient of reflectivity. The approach however may fail at large distances or in the case of mixed (sea clutter mixed with rain) situations. Chaff (i.e. synthetic fibers released from military aircraft), is not observed as frequently but can take the appearance as a fine line or even as an intense cell on Z_H images. Interferences from other transmitting sources are a major problem because they are really difficult to identify in real-time. They usually look like spirals of low-to-moderate reflectivity intensity (less than 30 dBZ). With the deployment of ever denser telecom networks and despite the restrictions on the band widths, interferences tend to be more and more frequent across Europe. Clear air echoes are caused by insects, dust, and turbulence. They are usually limited to the boundary layer (100 – 1500 m) and their intensity can be as high as 25 dBZ. They are a major problem in the summer when their occurrence in the lowest layers is around 80% (Tabary et al., 2005). They constitute an obstacle that hampers the use of radar data in NWP (Numerical Weather Prediction). Despite efforts to use all the radar parameters, satellite images, surface data, there is so far no way to efficiently filter out clear-air echoes.

A fuzzy-logic algorithm was developed in order to dynamically partition the image into rain and no rain parts (Gourley et al, 2006d). The four most informative dual-polarization variables are:

- The texture of the differential phase - tex(Φ_{DP}),
- The texture of the differential reflectivity - tex(Z_{DR}),
- The co-polar correlation coefficient - ρ_{HV}(0),
- The linear depolarization ratio - LDR.

The texture of a variable (x) is computed in a box consisting of three pixels in azimuth direction (m) and three in range direction (n) centered on the gate, as follows:

\[
\text{Texture}(x_{a,b}) = \sqrt{\frac{\sum_{i=-(m-1)/2}^{(m-1)/2} \sum_{j=-(n-1)/2}^{(n-1)/2} (x_{a,b} - x_{a+i,b+j})^2}{(m)(n)}}
\]

where \(a\) and \(b\) represent the azimuth and range of the gate.
Figure 6.1: Statistical distribution of (a) correlation coefficient, (b) texture of differential reflectivity, (c) texture of differential phase for different kinds of backscatterers – derived using data from the Trappes radar, and (d) linear depolarization ratio for precipitation and ground clutter – derived using data from the Thurnham radar.
In first instance, the signature of each type of artifacts must be categorized. It is important to note that no thresholding on polarimetric variables is used during this procedure. This enables the derived membership functions to remain unconditional and objective. Figure 6.1 shows the statistical distribution of the four most informative dual-polarization variables which include: $\rho_{HV}(0)$, LDR, and the texture of $Z_{DR}$ and the texture $\Phi_{DP}$. All distributions in Figure 6.1 have been normalized. It clearly shows that clear-air, chaff and ground-clutter echoes have a very distinct signature from precipitation echoes. Precipitation echoes have a very smooth structure, which gives much smaller texture values than clear-air, chaff and ground-clutter. Figure 6.1 also shows that the texture of $\Phi_{DP}$ provides the best discrimination between precipitation and non-meteorological backscatter. Figure 6.2 shows an example of reflectivity data processed using the information provided by the texture of $\Phi_{DP}$. These data were collected by the Thurnham radar under anticyclonic clear sky condition. During that event, the radar was detecting backscatters from the north coast of France (extending south to east of the PPI), from the North Sea (east of the PPI), and from clear air particles (north-east of the PPI). This example highlights the strength of the texture of $\Phi_{DP}$ at correctly deleting sea clutter and anaprop backscatters, and its weakness at handling clear air returns.

![Image](image.png)

**Figure 6.2:** Reflectivity in dBZ collected at Thurnham on 18 July 2006 at 23:34: (left) raw reflectivity; (right) reflectivity processed using a threshold on the texture of $\Phi_{DP}$.

### 6.2. Fuzzy logic algorithm

The goal of this fuzzy logic algorithm is to incorporate polarimetric quantities (i.e., $\rho_{HV}(0)$, texture of $Z_{DR}$, and texture of $\Phi_{DP}$) to determine whether the measurement is made in a precipitation medium or is contaminated by non-precipitating echoes. At each pixel, the summed probability ($Q$) is calculated for each $i^{\text{th}}$ class i.e., clear air echoes, ground clutter and precipitation, as follows:
where $P$ is the probability given the $j^{th}$ polarimetric quantity i.e. $p_{HV}(0)$, texture of $Z_{DR}$, and texture of $\Phi_{DP}$. The probabilities are simply looked up from the membership functions computed previously. For example, if the observed correlation coefficient is 0.97, then the probability of the pixel ($P_1$) being precipitation is 1.0, 0.15 for ground clutter, and 0.02 for clear air echoes. The summed probability ($Q_i$) is then calculated for each $i^{th}$ class given probabilities corresponding to the texture of $Z_{DR}$ and texture of $\Phi_{DP}$ (i.e., $P_2$ and $P_3$). The class is assigned according to the maximum value of the summed probabilities.

A preliminary analysis should be run before applying the “pure” fuzzy-logic scheme. The aim of that analysis is avoid unrealistic diagnostics. For instance, if the radial velocity is not zero, then we can assume that we are not dealing with ground-clutter. The table 6.1 summarizes the set of thresholds that are used in the preliminary analysis by Météo-France.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Thresholds</th>
<th>Suppressed Class Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_{HV}(0)$</td>
<td>&lt; 0.7</td>
<td>Precipitation</td>
</tr>
<tr>
<td>$\Phi_{DP}$</td>
<td>&lt; - 40°</td>
<td>Precipitation</td>
</tr>
<tr>
<td>$Z_H$</td>
<td>&lt; 5 dBZ</td>
<td>Precipitation</td>
</tr>
<tr>
<td>Texture of $\Phi_{DP}$</td>
<td>&gt; 100°</td>
<td>Precipitation</td>
</tr>
<tr>
<td>Pulse-to-pulse variability of $Z_H$</td>
<td>&gt; 5 dB</td>
<td>Ground Clutter</td>
</tr>
<tr>
<td>Radial velocity</td>
<td>&gt; 5 m s$^{-1}$</td>
<td>Ground Clutter</td>
</tr>
<tr>
<td>$Z_H$</td>
<td>&gt; 30 dBZ</td>
<td>Clear Air Echoes</td>
</tr>
</tbody>
</table>

Table 6.1: Threshold used by Météo-France during the preliminary identification of non-weather echoes.

The efficiency of the algorithm was evaluated by examining three different cases that span 1-24 hours. Reflectivity values in the algorithm-identified precipitating regions are converted to rainfall rate estimates using the Marshall-Palmer Z-R relationship (i.e., $Z=200R^{1.6}$) and accumulated over the event duration (Marshall and Palmer 1948). In order to assess the potential impact of non-precipitating echoes on rainfall accumulations, reflectivity from algorithm-identified non-precipitating echoes are converted to rain rates and accumulated in the same manner as precipitating echoes. The sum of the precipitation and non-precipitation accumulation fields shows the result if no data quality checks were performed on reflectivity data. The accumulation maps from precipitating and non-precipitating echoes are then compared for a case that had no precipitation but significant ground clutter and anomalous propagation, a predominately widespread rainfall case with a small region of ground clutter, and a case with intense convection, clear air echoes, and ground clutter. It is recognized that this evaluation
methodology does not have the benefit of a ground truth data set. However, the evaluation is performed over several hours for cases that were carefully studied in order to understand the various sources of the echoes.

6.2.1. **Dry weather event with ground clutter and anomalous propagation:**

Classification results were produced every 15 min from 14 to 20 UTC on 15 Jan 2005 using data collected at an elevation angle of 0.4°. Accumulations from algorithm-identified precipitating echoes and potential accumulations from non-precipitating echoes are compared. The impact of reflectivity from algorithm-identified ground clutter and anomalous propagation on rainfall estimates is shown in Figure 6.3a. The polarimetric fuzzy logic algorithm could be judged as perfectly skillful only if there were no accumulations from precipitation echoes. It is noted, however, that several pixels in ground clutter and anomalous propagation regions are misclassified as being precipitation (Figure 4.3b). The isolated nature of these misclassified pixels suggests a Doppler velocity filter or even a simple spatial smoothing filter could be implemented to achieve higher probabilities of detecting non-precipitating echoes.

6.2.2. **Widespread rainfall event with a small region of ground clutter:**

The polarimetric fuzzy logic algorithm classified precipitating and non-precipitating echoes for 12 scans of data at an elevation angle of 1.5° from 04 to 05 UTC on 04 Jul 2005. Movie loops of the polarimetric variables were analyzed to determine the sources of the echoes. This case was dominated by widespread rainfall, but a small region of ground clutter was noted near the radar. Echoes from ground clutter were identified from the movie loops because they remained stationary. Figure 6.3c shows rainfall accumulations that would have resulted from non-precipitating echoes. Isolated pixels from ground clutter within 10km of the radar would have contributed as much as 100mm to an hourly rainfall accumulation map. There are accumulations less than 0.25mm from supposed non-precipitation echoes in an annulus centered at 100km in range. Reductions of $\rho_{HV}(0)$ values in the melting layer, which was encountered near 100km in range, resulted in isolated pixels to be misclassified as non-precipitation. This small error, which is nearly negligible, will be corrected by automatically identifying the melting layer such as in Brandes and Ikeda (2004). Vertical profiles of temperature also indicate the height and depth of the melting layer. Values of $\rho_{HV}(0)$ are also reduced when hail is mixed with rain. The weight on $\rho_{HV}(0)$ should thus be reduced when hail is suspected (e.g. based on observations of high $Z_H$ and low $Z_{DR}$).

Non-precipitating echoes were incorrectly identified in a raining region between 200 and 250 km in range. Beam heights exceeded 5km at these long ranges, thus the radar was observing reflectivity values $< 10$dBZ associated with ice. As shown in the Table 6.1, precipitation classifications are not permitted with echoes that have reflectivity $< 5$dBZ. In effect, the polarimetric fuzzy logic algorithm was useful up to a range of approximately 200km with this case. The range at which the algorithm is effective improves with lower radar elevation angles and with storms that have deep profiles of reflectivity.
Figure 6.3: Radar estimates of rainfall in mm from algorithm-identified a) non-precipitating echoes and b) precipitating echoes from 1400-2000 UTC 15 Jan 2005 (i.e. Dry weather event with ground clutter and anomalous propagation), c) non-precipitating echoes and d) precipitating echoes from 0400-0500 UTC 04 Jul 2005 (i.e. Widespread rainfall event with a small region of ground clutter), e) non-precipitating echoes and f) precipitating echoes from 0000-2345 UTC 23 Jun 2005 (i.e. Intense convective event clear air echoes, and ground clutter). Rainfall estimates were computed using $Z=200R^{1.6}$.

Figure 4.3d shows accumulations from reflectivity observed in algorithm-identified precipitating echoes. The pattern of accumulations reveals no noticeable artifacts that would have resulted from non-precipitating echoes that were not adequately removed. Some isolated pixels within 5km of the radar, however, have zero accumulations. These pixels were identified as ground clutter and thus created small holes in the rainfall accumulation field. These holes will
be mitigated by spatially interpolating data from nearby pixels that were classified as precipitation.

6.2.3. Intense convective event clear air echoes, and ground clutter:

The fuzzy logic algorithm identified non-precipitating and precipitating echoes for 96 scans of data collected at an elevation angle of 1.5° from 0000-2345 UTC on 23 Jun 2005. Figure 6.3e shows accumulations that would have resulted if echoes from ground clutter, clear air, and solar radiation were not removed. Reflectivity from ground clutter within 5 km of the radar results in accumulations exceeding 200m at several pixels. Reflectivity from clear air echoes results in accumulations less than 1mm extending out to a range of 60km. The impact of clear air echoes on radar rainfall estimates is not as significant as with ground clutter, but these echoes cover a large region and will bias long-term (e.g. daily or monthly) rainfall accumulations. Accumulations from precipitating echoes depict no noticeable artifacts near the radar resulting from clear air echoes or ground clutter (Figure 6.3f).

6.3. Recommendations and operational considerations:

On the basis of studies carried out by Météo-France (using fuzzy logic) and by the UK Met Office (using thresholds on tex(\(\Phi_{DP}\)), on \(\rho_{HV}(0)\), or on LDR), the following recommendations can be drawn:

- Texture of \(\Phi_{DP}\) offers the best discrimination between precipitation and non-weather echoes. In particular, it enables a clear separation between sea clutter and precipitation echoes.
- Most artefacts are characterized by low \(\rho_{HV}(0)\). However intense clutter echoes tend to have a high \(\rho_{HV}(0)\) value. Furthermore precipitation echoes may also be associated with lower \(\rho_{HV}(0)\) values due to low SNR at long range. Therefore care must be taken when applying a threshold using \(\rho_{HV}(0)\) values.
- LDR is also very informative in distinguishing between precipitation and non-precipitation echoes. However, LDR measurements require a special scan transmitting waves in H and receiving H and V.
- Texture of \(Z_{DR}\) does not offer much more information than the other parameters.
- A fuzzy-logic algorithm (Gourley et al, 2006d) is well suited and computationally viable to make the synthesis of all available measurements in real-time. It does require however a thorough preliminary analysis in order to avoid unrealistic diagnostics.
7. Bright-band Identification

Bright band has always been recognized as a major source of error in radar Quantitative Precipitation Estimation (QPE) especially in the winter time (Zawadzki 1984). Furthermore, rain/snow discrimination which is a necessary step prior applying appropriate Z–R relationships and/or polarimetric algorithms (such as rain-profiling algorithms), often depends on the identification of the bright band. Over the years, many operational services have introduced real-time Vertical Profile of Reflectivity identification and correction procedures (e.g. Koistinen 1991, Tabary 2006). However, bright band is not always easy to recognize on conventional reflectivity images because of the large variability of the horizontal reflectivity field and because of beam smoothing. Dual-polarization clearly offers new perspectives in that regard.

Several studies have permitted to document the values of polarimetric variables in the bright band at S (e.g. Zrnic et al. 1993, Smyth and Illingworth 1998, Brandes and Ikeda 2004; Ikeda et al. 2004; Giangrande et al. 2005) and C-band (Baldini and Gorgucci 2006). The melting layer is usually associated with an enhancement of the horizontal reflectivity (Z_H), differential reflectivity Z_{DR} and a decrease of the co-polar correlation coefficient (\rho_{HV}). Due to large melting snowflakes, backscattering effects may induce enhanced differential phases (\Phi_{DP}). The LDR parameter, when available, also shows an increase in the melting layer. The magnitude of the variations experienced by the polarimetric parameters is quite variable. Using field campaign results and long-term observations, Brandes and Ikeda (2004) model the magnitude of the variations in the melting layer as follows: +8 dB for Z_H, +9 dB for LDR, \rho_{HV} value decreasing to 0.92. The following figure shows the PPIs of the polarimetric variables obtained on a stratiform day by the Trappes radar. The concentric pattern of the bright band makes its identification quite obvious.

Twenty episodes of stratiform precipitation observed with the French C-band Trappes radar were selected over the period December 2004 – March 2006. The retrieval of the vertical profile of polarimetric variables was carried out using only the 9° tilt, which the highest “almost horizontal” tilt of the Trappes Volume Coverage Pattern. That tilt is revisited every 15 minutes. The Trappes Volume Coverage Pattern also includes a 90° tilt but it is essentially used to calibrate Z_{DR}. Radar data at 9° were corrected for ground-clutter and other non-precipitating echoes using a fuzzy logic algorithm (Gourley et al. 2006d). Care was taken not to remove the bright band signature, which, as will be seen later, share some common characteristics – in terms of \rho_{HV} and textures – with ground clutter. Low-SNR data (less than 10 dB) were flagged and subsequently removed. Values of correlation coefficient were corrected for low-SNR bias. Differential reflectivity was corrected for a system bias (see section 4.6), and \Phi_{DP} for the system differential phase (-6.5°) and azimuthal interferences. Likewise, only pixels having a reflectivity above 10 dBZ were considered. The vertical profile of each variable (Z_H, Z_{DR}, \Phi_{DP} and \rho_{HV}) was then obtained by averaging the remaining quality-controlled data across all azimuths. The estimation of the mean at a given height was validated if at least one fourth (i.e. 180) of the pixels were available. A set of 314 profiles were obtained. In order to make them comparable,
those profiles have been referenced along the vertical with respect to the minimum in $\rho_{HV}$ (i.e. middle of the bright band). Similarly the vertical profiles of $Z_H$ and $Z_{DR}$ have been normalized by the value at ground level. Figure 7.1 presents the results of that climatology. All (normalized) have been put together (think black lines). The mean +/- standard deviation profiles have been superimposed.

Figure 7.1: Climatology of the vertical profiles of $Z_H$, $Z_{DR}$, $\rho_{HV}$ and $\Phi_{DP}$, observed with the Trappes radar between December 2004 and March 2006. The mean (green curve) +/- standard deviation (pink curves) have been added.

A bright band identification algorithm was proposed by Tabary et al. (2006), based entirely on $\rho_{HV}$, mainly because the added value of the other parameters was considered to be negligible: the horizontal variability of $Z_H$ and $Z_{DR}$ quite often blurs the bright band signature and makes them useless for melting layer identification, especially when data from low-elevation
angles are considered. The current version of the algorithm assumes that the bright band characteristics (bright band height and bright band thickness) are the same all around the radar. It is also assumed that the intrinsic profile of $\rho_{HV}$ can be modeled very simply with two parameters: the freezing level height (i.e. the top of the bright band) and the bright band thickness. Figure 7.2 illustrates that simple conceptualization.

![Figure 7.2: A simple model for the intrinsic vertical profile of $\rho_{HV}$.](image)

Data gathered at all N elevation angles of the Volume Coverage Pattern are quality controlled (i.e. corrected for ground-clutter, low SNR, clear air, birds, insects, …) and then averaged for each 240 m range across all available azimuths to yield a set of N mean radial curves of $\rho_{HV}$ ($\rho_{HV}^{OBS}(r)$). Averaging across all azimuths aims at enhancing the bright band signature. On the other side, a set of $\rho_{HV}$ profiles are generated by letting FLH and BBT vary within reasonable ranges. FLH typically vary between 0 and 4000 m with 200 m increments and BBT between 200 m and 1000 m with 200 m increments. For each candidate profile, a set of simulated $\rho_{HV}^{SIM}(r)$ radial curves are generated. The effect of beam smoothing is taken into account in that process. The observed and the simulated $\rho_{HV}(r)$ profiles are compared and the (FLH,BBT) couple that is selected is the one that leads to the best agreement between the profiles. Figure 7.3 presents an example of observed and simulated $\rho_{HV}(r)$ profiles:
Figure 7.3: Observed (left) and simulated (right) $\rho_{HV}(r)$ profiles during a stratiform day.

The algorithm has been tested using 20 rather stratiform events. The top of the identified melting layer has been systematically compared with independent aircraft measurements. Overall, the agreement is excellent, both in terms of correlation and mean difference. Figure 7.4 presents a comparison between the radar-derived top and bottom of the bright band (triangles), the aircraft 0°C height measurements (blue line) and the Trappes radiosonde FLH (black curve).

![Graph showing FLH detected and FLH from RS and AMDAR 20050704](image)

Figure 7.4: Comparison between radar-derived top and bottom of the bright band, aircraft measurements and radiosonde 0°C height on a particular day.

In conclusion, it is clear that dual-polarization parameters, and especially the $\rho_{HV}$ parameter, contain valuable information regarding the bright identification issue. The choice and development of an identification algorithm is clearly of secondary importance.
8. Considerations on Partial Beam shielding effects on dual polarisation parameters

Rainfall estimates from polarimetric variables are most commonly based either on reflectivity (i.e. $Z_H$ and $Z_{DR}$), $K_{DP}$, or combinations. Phase measurements are absolute measurements which are not affected by partial beam blockages (Zrnic and Ryzhkov 1996). Figure 8.1 shows rainfall accumulations based on $Z_H$ and $K_{DP}$ measurements. Although large differences in rainfall accumulation occurred with the different methods, artifacts resulting from radar beam shielding (regions within black arrows and dashed lines in Figure 8.1a) are more evident in the accumulations from the $Z_H$ method.

Figure 8.1: Rainfall accumulation on 4 July 2005 between 0000 and 0600 UTC at 0.4° elevation angle using radar rainfall algorithms based on (a) $Z_H$ and (b) $K_{DP}$, respectively. Regions of high radar beam shielding are indicated with black arrows and dashed white lines in (a) and show a pronounced decrease in rainfall accumulation compared to the same regions shown in (b). The investigation area is limited to a range of 5 to 100 km around the Trappes radar located in the center.

The behavior of the polarimetric variables is shown as a function of beam shielding in Figure 8.2. Median values of $Z_H$ are reduced by ~4 dB for a power loss due to beam blockage of 6 dB. This is significant knowing the precision in $Z_H$ needed for rainfall rate estimation is 1 dB. The polarimetric variables $Z_{DR}$ and $K_{DP}$ are less affected by beam shielding for losses up to 6 dB. Their median values vary within the experimentally found precision of 0.2 dB for $Z_{DR}$ and 0.1° km$^{-1}$ for $K_{DP}$ (Gourley et al. 2006b). When more then 70% of the beam is shielded $Z_{DR}$ and $K_{DP}$ become noisy.
Figure 8.2: Variations of $Z_H$ (black), $Z_{DR}$ (dark gray), and $K_{DP}$ (light gray) as a function of power loss and beam shielding. Medians for each beam shielding class (every 1%) are indicated as thin lines; the centered averaged medians including ten beam shielding classes are overlaid as thick lines.

In the case of beam shielding, a weaker transmitted signal reaches precipitation at further ranges resulting in a reduced backscattered signal. Unbiased phase measurements are possible in these shielded regions where the backscattered signal has been reduced. However, in order to measure small $\phi_{DP}$ changes in light rain high accuracy is required. Although an accuracy of $\pm 3^\circ$ for $\phi_{DP}$ can be achieved theoretically (see section 3), in practice $\phi_{DP}$ values are contaminated by several factors. Blackman and Illingworth (1993) showed that obstacles cause large, random differential phase shifts. Illingworth (2003) quantifies this phase noise to be $\pm 5^\circ$ when a random phase is added to precipitation which has a backscatter amplitude ten times larger.

Figure 8.3: Schematic diagram summarizing the results of this study. Thick black lines illustrated the behaviour of $R(Z_H)$, $R(Z_{DR})$, and $R(K_{DP}, Z_{DR})$ with respect to $R(K_{DP})$. The results are based on four rainfall events with different rainfall characteristics. Gray line indicates the reflectivity correction most commonly applied to radar reflectivity.

The influence of radar beam shielding on reflectivity- and $K_{DP}$-based rainfall estimates was investigated with data obtained by the Trappes radar (Friedrich et al., 2006). The analysis
was based on four typical rain events encountered in Europe including a cold frontal rain bands with average rainfall of <5 mm h$^{-1}$ in winter, and one event with average values of 10 – 30 mm h$^{-1}$ in summertime. Also two summertime events with stratiform precipitation and embedded convection with local maxima in rainfall of ~50 mm h$^{-1}$ were part of the analysis. Nine combinations of rainfall estimates consisting of three drop-size distributions and three axis-ratio parameterizations were assessed. Although the rainfall estimates were sensitive to drop-size distribution and axis-ratio parameterization, the trends occurring with increasing beam shielding were independent from these parameters.

The influence of beam shielding on $R(Z_H)$, $R(Z_H, Z_{\text{DR}})$, and $R(K_{\text{DP}}, Z_H)$ are summarized in Figure 8.3. Large effects of beam shielding on rainfall accumulation were observed for $R(Z_H)$ and $R(Z_H, Z_{\text{DR}})$ with differences up to ~2 dB (40 %) compared to $R(K_{\text{DP}})$ over a beam shielding range of 0 – 8 dB. In two out of four events the strongest decrease in $10\log_{10}[R(Z_H)/R(K_{\text{DP}})]$ and $10\log_{10}[R(Z_H, Z_{\text{DR}})/R(K_{\text{DP}})]$ occurred between 0 – 1.5 dB. Only small effects ($\pm$ 0.5 dB) occurred for $R(K_{\text{DP}}, Z_{\text{DR}})$ compared to $R(K_{\text{DP}})$. Large variability in the polarimetric variables occurred for power losses > 6 dB (75 % beam shielding) increasing tremendously for power losses larger than 8 dB (~85 % beam shielding).
9. Conclusions and Recommendations

At present, there are about half a dozen C-band dual polarization radars in operational use by NMS across Europe. The polarimetric parameters available are: $Z$, $Z_{DR}$, $\Phi_{DP}$, $\rho_{HV}$, and LDR. Because most of those radars are transmitting simultaneously the H and the V waves, they do not provide LDR simultaneously with the other dual-polarization variables. Special cans can be dedicated to the acquisition of LDR. Some radar only provides $Z$ and $Z_{DR}$ although recent installations generally provide the full set of parameters.

The aim of this report work was to analyze the potential problems arising from the use of dual-polarization in an operational context. Dual-polarization is a technology that provides more (actually more than twice as many) parameters than conventional technology. It is clear to everybody that those parameters clearly contain very valuable information for many radar applications and products. For those variables not to be detrimental for the operational products, NMS has to implement rigorous and continuous quality control procedures on the data. In this work, we have tried to design a series of tests and indicators that can help checking the quality of the raw dual-polarization variables.

The first “health” check regarding the quality of the dual polarization parameters that NMS should carry out upon purchasing a new radar is to estimate the peak value of $\rho_{HV}(0)$ in rain. This analysis may highlight potential problems with the radar system and will define the overall measurements accuracy that can be expected from the polarimetric variables.

The monitoring of the bias on the $Z_{DR}$ parameter may be achieved by performing a vertical scan on a regular basis. Currently such scans are performed every 10 and 15 minutes, respectively, at the UK Met Office and at Météo France. More intelligent (adaptive) scan strategies may help reducing the mechanical strain. The $Z_{DR}$ biases for the French and the UK radars were found to be remarkably constant over time. The required precision of 0.1 dB (for quantitative use of $Z_{DR}$) can be achieved.

The system differential phase – often denoted by $\Phi_{DP0}$ – should also be monitored even in the case when it is not used directly in attenuation correction procedures, some recommending normalizing each $\Phi_{DP}$ profile by the first valid value along the ray. At Météo France, the system differential phase – and more particularly its sudden changes - turned out to be a very good indicator of potential problems in the radar systems.

An interesting outcome of the present work is the characterization of the (alleged) impact of the radome on the dual-polarization variables. A very large percentage of European radars have a radome so that problem has to be taken care of. The analysis of $Z_{DR}$ and $\Phi_{DP0}$ as functions of the azimuth has revealed wave-like features with a number of periods that correspond to the number of peels. As the disturbances are stationary, empirical corrections have been determined.
and applied. It is clear however that that impact will have to be more precisely analyzed in the future.

Dual-polarization variables allow making significant and immediate progress on 1) non-precipitation echo removal, 2) attenuation correction, 3) bright-band identification. We have verified that very simple and robust procedures can be designed in those three areas. More complex and efficient schemes will probably be proposed in the future but the main benefits are already available. Within the frame of the present work we did not have time to perform in-depth analysis of the operational potential of dual-polarization for 1) radar calibration, 2) QPE, 3) hail detection and 4) use in mountainous regions which are important issues for many radar data users across Europe. Nothing in our preliminary work indicates that no improvement is to be expected in those four domains.
References


