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Evaluation of dual polarization technology at C-band for operational weather radars as part of the EUMETNET OPERA programme

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1 Introduction

Over the past 5 years, several National Met. Services (NMSs) in Europe have started introducing polarimetry into their C-band radar networks; among them are France, Germany, Hungary, Italy, Slovenia, Sweden, and the UK. Evaluation of the benefits of dual-polarization is progressing slowing and is so far proving positive, although no NMSs are yet operationally using dual-polarization derived products. As part of the EUMETNET OPERA programme, a report was commissioned to gather results of scientific experiments on C-band dual polarization radars from NMSs across Europe. The full report deals with issues that are specific to the use of polarimetry at C-band including: How do attenuation correction schemes perform? How does the scheme for absolute calibration of Z perform? What are the benefits of dual polarization for identification of non-hydrometeors? What are the benefits of polarimetry on rainfall rates estimates (R)? This paper presented a brief summary of this report. The full report can be obtained through the OPERA web site: www.chmi.cz/OPERA/, or the authors.

2 Hardware specifications

Two radars were used in the studies reported in this paper: one operated by Météo-France; the other operated by the UK Met Office. Both radars are equipped with linear polarization capabilities transmitting waves polarized at 45^o and receiving H and V separately through two channels. Table 1 gives a summary description 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. Both radars have the capability to measure the reflectivity (Z_H or Z_V), the differential reflectivity (Z_{DR}), the phase (ϕ_{DP}) and the amplitude of the cross-correlation coefficient at zero lag ($\rho_{HV}(0)$), the linear depolarization ratio (LDR), and the Doppler moments.

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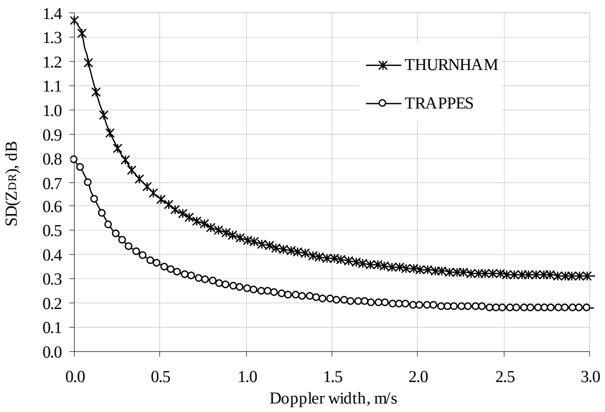
3 Individual parameters evaluation

3.1 Measurements accuracy

The accuracy of the measurements of polarimetric parameters is of prime importance in term of improving rainfall estimates. In particular, Z_{DR} should be accurate to 0.2 dB for R(Z,Z_{DR}) algorithms (Illingworth, 2003). The accuracy of the parameters is limited by the number of samples used in the estimate, the variety of drops in the sample volume, and the magnitude of the co-polar correlation coefficient (Bringi and Chandrasekar, 2001). The quality of the data may be evaluated through comparison of measured and theoretically estimated standard deviation of the variables. As illustrated by Figure 1, Z_{DR} measurements performed by the Trappes radar are expected to be of better accuracy than those collected by Thurnham due to its high value of co-polar correlation coefficient i.e. peak value of $\rho_{HV}(0)$ recorded in rain is 0.99 at Trappes and 0.965 at Thurnham. The cause for these lower values of $\rho_{HV}(0)$ observed at Thurnham is currently under investigation.

Table 1. Characteristics of the operational C-band dual-polarization radar operated by Météo-France and by the UK Met Office.

Radar site Name	Trappes	Thurnham
Location	SW Paris	SE London
Radar Manufacturer	Gematronik	EEC
Antenna Type	Centre-fed	Centre-fed
Diameter	3.7 m	3.7 m
Beam width	< 1.1^o	< 1.0^o
Peak power	250kW	250kW
Pulse width	2 µs	2, and 0.4 µs
Receiver location	Control room	Back of the antenna
Dynamic range	> 95 dB	~ 100dB
Signal Processor	CASTOR2 by Météo-France	EDRP9 by Lassen and EDGE by EEC



(a) Variation of the standard deviation of differential reflectivity

Fig. 1. Theoretical variation of the standard deviation of the differential reflectivity with the Doppler spectrum width. The value of $\rho_{HV}(0)$ used in the analysis is 0.965 for Thurnham, and 0.99 for Trappes.

Observed standard deviations may be computed by using nine-gate windows along a radial. Larger windows would increase the precision of the standard deviation but would also increase the value of the standard deviation due to natural variability. Furthermore, an altitude threshold should be imposed to restrict sampling below the bright-band i.e. sampling only precipitation in liquid phase. Finally, the dataset should be limited to data associated with ϕ_{DP} less than 10^o to avoid bias caused by attenuation. Table 2 shows a comparison of the observed and theoretical standard deviation for Z_{DR} in rain. These results suggest that Z_{DR} measurements performed by the Trappes radar are of sufficient accuracy to be used in $R(Z,Z_{DR})$ algorithms. At Thurnham, Z_{DR} data may need to undergo some averaging to reach the required accuracy.

3.2 Offset calibration of the differential reflectivity

Z_{DR} offset may be caused by hardware differences between the horizontal and vertical channels. Scattering properties of raindrops at vertical incidence are of equal power in both polarizations, resulting in Z_{DR} values expected to be 0 dB. Thus, measurements collected at vertical incidence in rain provide the opportunity to examine the absolute calibration of Z_{DR}. Mean canting of raindrops or an imprecise pointing angle may lead to more variable Z_{DR} measurements, therefore the offset should be computed from an average across azimuth. Using this procedure, Z_{DR} offset was found to be – 0.16 ± 0.60 dB with a reproducibility from scan to scan of ± 0.03 dB for Thurnham (Figure 2), and – 0.08 ± 0.90 dB for Trappes.

Table 2. Comparison between theoretical and observed precision errors for Z_{DR} (for non-normalized spectrum widths value of 2 m/s, with for $\rho_{HV}(0)$ values of 0.99 ± 0.01 for Trappes radar and 0.965 ± 0.01 for Thurnham radar).

Parameters	Theoretical standard deviation	Observed standard deviation
Differential reflectivity:		
Thurnham	± 0.45 dB	± 0.61 dB
Trappes	± 0.20 dB	± 0.21 dB

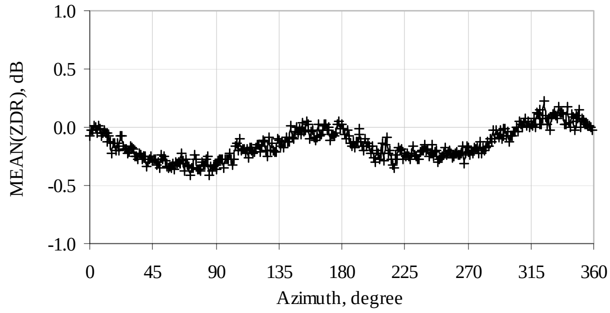


Fig. 2. Z_{DR} calibration diagrams derived from data collected in rain at vertical incidence by the Thurnham radar

Solar radiation are of equal power at both horizontal and vertical polarizations, thus detection of solar radiation when the sun crossed the radar beam near sunrise and sunset may also be used for determining Z_{DR} offset. Solar radiation along a radial can be automatically found according to the following criteria:

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

Figure 3 shows a frequency distribution from the sun spike produced using a dataset collected at Trappes. The curve is approximated well a normal error distribution with a slightly negative mean of –0.2 ± 1.4 dB. Both Z_{DR} calibration methods are in agreement for the Trappes radar.

Measurements of Z_{DR} offset using the detection of solar radiation have the advantage of making use of redundant data and not requiring scans specially set aside for calibration. However, 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 only tests 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.

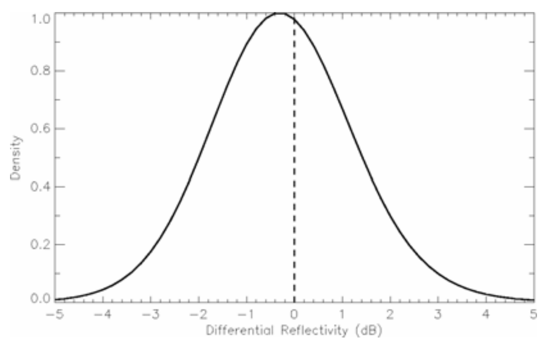


Fig. 3. Z_{DR} calibration diagrams derived from solar radiation collected by the Trappes radar

4 Absolute calibration of reflectivity

Dual polarization technology provides a novel approach to Z calibration 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). K_{DP} can be estimated 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 ϕ_{DP}. Differences between measured and computed ϕ_{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 prior calibrated and should be free of azimuthal dependency due to near radome interference.
- ϕ_{DP} should be corrected for initial system offset and should be free of azimuthal dependency due to the wave guide rotary joints.
- ϕ_{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 ϕ_{DP} values lower than 10^o.
- 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.

Gourley and Illingworth (2005) concluded that the Trappes radar was miscalibrated by -1dB, and reported excellent results between observed and derived ϕ_{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.

5 Non-weather echo identification

The availability of dual-polarization variables provides a very good opportunity to improve artefact identification and removal. Gourley et al (2006b) developed a fuzzy-logic algorithm to dynamically partition the image into rain and no rain parts. 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 - $\rho_{HV}(0)$,
- The linear depolarization ratio - LDR.

where 'texture' refers to the standard deviation between a polar cell and its eight surrounding neighbours. This term has proven very useful as precipitation echoes have a very smooth structure, which gives much smaller spatial variability than clear-air, chaff and ground- and sea-clutter.

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

- Texture of ϕ_{DP} offers the best discrimination between precipitation and non-weather echoes. In particular, it enables a clear separation between sea clutter and precipitation echoes otherwise not permitted by the other parameters.
- 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, 2006b) 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.

6 Attenuation correction

Many studies have shown that the differential phase is a very good indicator of Path Integrated Attenuation (PIA) in rain. Gourley et al. (2005) developed a method to verify the PIA = $f(\phi_{DP})$ relationship based on the assumptions that:

- The azimuths of attenuated sectors are changing rapidly with time, as attenuating convective cells pass through the radar domain.
- The main source of variation between two successive but synchronized radar images (i.e. corrected for advection) is attenuation. In convective situation, there may be growths and decays of the cells, but on average those effects should cancel out.

Under those assumptions and with some linear algebra, an empirical PIA = $f(\phi_{DP})$ curve may be estimated. Météo-France ran an experiment using 7 severe convective cases. Figure 4 shows the results obtained as a function of differential attenuation (A_{DP}). All curves are linear and within theoretical limits. The observed variability is known to be due to temperature and DSD.

An attenuation correction procedure performed by ZPHI was assessed by means of radar-rain gauge comparison. Figure 5 shows the normalized bias of the ZPHI and conventional rain rate estimators as functions of the mean attenuation over the hour. The normalized bias of the conventional estimator becomes clearly negative at high (mean) attenuations while that of the ZPHI estimator remains stable.

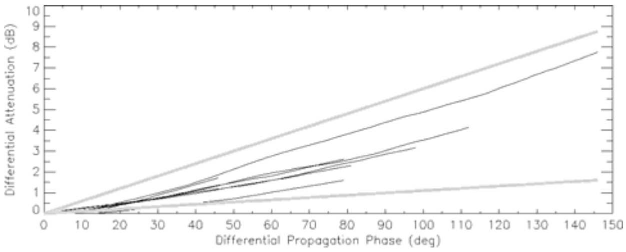


Fig. 4: Differential attenuation as a function of the differential phase: one curve per episode (in black); theoretical limits (grey lines).

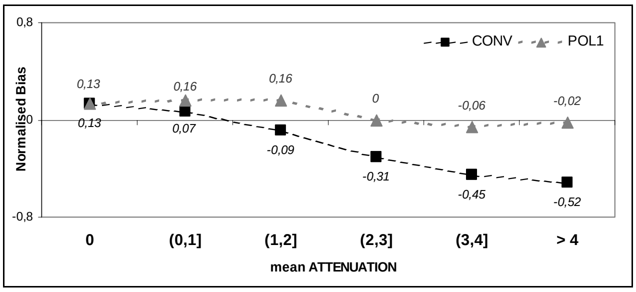


Fig. 5: Normalized bias of the ZPHI and conventional rain rate estimator as functions of the mean attenuation over the hour.

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.

7 Conclusions

This paper summarises experiments carried out by Météo-France and the UK Met Office in attempts to deal with issues that are specific to the use of polarimetry at C-band for operational purposes. Most key issues are still under investigation but preliminary results are very encouraging.

The operational use of polarimetric variables requires well defined and continuously monitored quality indicators. At this stage, the main benefits of dual polarization for NMS are believed to lie with the improvement of the absolute calibration of Z, with the improvement of the attenuation correction, and with the identification of non precipitation echoes. It is not yet clear however, how much benefits polarimetric QPE algorithms (e.g. $R(Z,Z_{DR})$, $R(Z,Z_{DR},K_{DP})$ or ZPHI by Testud et al. 2000) will bring in the long run. Indeed, such algorithms require rigorous identification of the hail spots and of the bright band. The latter factor alone may limit the use of rainfall rate dual polarization algorithms to a maximum range of 60 km in the winter.

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