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Radar calibration using consistency of polarization parameters and constraints for drop shapes

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1 Introduction

The accuracy of radar-based rain rates is limited by the calibration of radar reflectivity (Z_H), which must be measured within 1 dB for rainfall estimates to have an accuracy of 15%. Several approaches to radar calibration have been undertaken which are summarized in Atlas (2002). The receive component of the radar can be calibrated using a transmitter with a known signal strength. Transmit and receive components can be calibrated jointly by positioning a reflective target with a known radar cross-section into the radar beam using aircraft, a balloon, etc. Another approach is to compare radar reflectivity to disdrometer measurements as in Joss et al. (1968). The relative calibrations of the US Weather Service Radar-1988 Doppler (WSR-88Ds) have also been explored by comparisons with space-borne radar (Bolen and Chandrasekar 2000) and neighboring WSR-88D radars (Gourley et al. 2003). None of these approaches has emerged as the standard procedure for calibrating radars.

More recently, polarimetric radar studies have shown that Z_H, differential reflectivity (Z_{DR}), and the range-derivative of differential propagation phase (Φ_{DP}), or specific differential phase (K_{DP}), are redundant in rain. This means that Z_H can be calibrated to match expected values obtained from measurements of Z_{DR} and K_{DP}. The approach shown by Goddard et al. (1994a) and Illingworth and Blackman (2002) assumed that raindrop spectra could be well represented by a gamma function and that raindrop shapes varied with size according to Goddard et al. (1994b). They found that K_{DP} normalised by Z_H (in mm6 mm-3) was a well-behaved function of Z_{DR} which was almost independent of the index of the gamma function. Using this function, a theoretical value of K_{DP} could be derived at each gate along the ray from the observed value of Z_H and Z_{DR}. The theoretical Φ_{DP} by integrating these values of K_{DP} along the ray was compared with the observed Φ_{DP}, and the difference between the two was attributed to miscalibrated Z_H. Another empirical approach is to derive a relationship between Z_H, Z_{DR}, and K_{DP} using an extensive set of raindrop spectra observed with a disdrometer (Ryzhkov et al. 2005). The same relations are used to estimate K_{DP} over a sufficiently large space-time domain using polarimetric radar observations of Z_H and Z_{DR}. Differences between observed and estimated K_{DP} are attributed to miscalibrated Z_H. Section 2 outlines the methodology of the approach using the total phase shift and discusses the various error sources that can either offset or enhance the apparent miscalibration in Z_H. Section 3 presents calibration results using polarimetric observations from MeteoFrance's C-band radar located 30 km to the southwest of Paris in Trappes.

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Currently, there is some doubt in the community regarding the correct model used to relate drop oblateness (represented as a drop aspect ratio) to equal-volume spherical diameter (D_e), especially for small drops with diameters from 0.5 – 1.5 mm. This study examines the sensitivity of calibration results to several raindrop shape models used in the literature. As it turns out, the sensitivity test in section 4 provides an additional constraint on the various drop shape models which have been proposed. Models using a simple linear slope parameter (*b*) linking drop oblateness to diameter are shown to be inadequate, whereas the Brandes et al. (2002) shapes are found to provide the most consistent calibrations. The choice of the correct drop shape model has a significant effect on attenuation and rainfall rates estimated from polarimetric radars.

2 Method to calibrate Z_H using consistency theory

In this study we provide a rigorous analysis of the Φ_{DP}-based approach proposed by Goddard et al. (1994a) and Illingworth and Blackman (2002). This technique is preferred to the empirical, K_{DP}-based approach because it avoids differentiating noisy Φ_{DP} profiles in light rain to produce an even noisier K_{DP} estimate. In addition, it was shown in Gorgucci et al. (1999) that K_{DP} can be biased either positively or negatively if the rainfall in the path over which K_{DP} is computed is nonuniform. The Φ_{DP}-based approach considers the difference between the total phase shift at the end of the ray computed from consistency theory and observations. The inherent noise in Φ_{DP} measurements is thus minimised by integration along the ray.

The goal of this technique to develop an automated procedure to compare the theoretical change in Φ_{DP}, $\Delta\Phi_{DP}(th)$, from the beginning to the end point of the rain path to the change in observed values, $\Delta\Phi_{DP}(obs)$. The technique is based on the calibration curve shown in fig. 1. The curve was produced by assuming natural raindrop shapes are represented by the Brandes et al. (2002) model and their spectra are represented by a normalised gamma distribution with a shape parameter (μ) of five and a drop temperature of 0˚C. At a temperature of 20˚C and once Z_{DR} > 1.5 dB the curve diverges from the 0˚C values so that for Z_{DR}=2 dB it is about 10% lower. Changes in calibration for μ in the range from zero to ten are insignificant. The Brandes model was chosen for the calibration experiment because its axis ratios agree well with the observations of Thurai and Bringi (2005) for drops between 1.5-7 mm. Radar measurements of Z_{DR} and Z_H are used to compute the theoretical K_{DP} using the curve in Fig. 1. The theoretical K_{DP} or $K_{DP}(th)$ is integrated along the ray to yield $\Phi_{DP}(th)$. The initial $\Phi_{DP}(th)$ is always zero, thus $\Phi_{DP}(th)$ is the same as $\Delta\Phi_{DP}(th)$. Finally, differences between $\Delta\Phi_{DP}(obs)$ and $\Delta\Phi_{DP}(th)$ at the end of the rain path are calculated and attributed to miscalibration in Z_H.

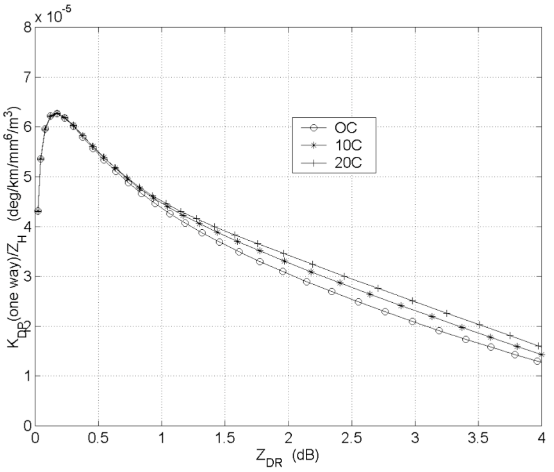

Fig. 1. Calibration curve assuming Brandes et al. (2002) raindrop shapes and their spectra are represented by a normalised gamma distribution with a shape parameter of five. Sensitivity to drop temperature is shown to be insignificant.

In developing this automated procedure, we encountered numerous data quality issues requiring correction. Details of the quality of the raw variables from the Trappes radar and correction methods are reported in Gourley et al. (2006a). First, a miscalibration in Z_{DR} of -0.08 dB was corrected using measurements at vertical incidence where the intrinsic Z_{DR} is known to be 0 dB. We also noticed that Z_{DR} values had an azimuthal dependence caused by structures situated in the near-field of the antenna. An empirical mask was developed and implemented to mitigate errors that were previously as large as 0.4 dB. Next, values of $\Phi_{DP}(obs)$ were dealiased by simply subtracting 360˚ if raw measurements exceeded 270˚. In order to compute the change in $\Phi_{DP}(obs)$ from the beginning to the end of the rain path, we had to determine the starting $\Phi_{DP}(obs)$. This value was found independently for each ray by computing the mean $\Phi_{DP}(obs)$ in a 25-gate or 6-km smoothing window. The same smoothing procedure was applied to all $\Phi_{DP}(obs)$ and $\Phi_{DP}(th)$ data along the ray. The standard deviation of raw $\Phi_{DP}(obs)$ was found to be 1.8˚ in rain, thus the smoothing reduced this noise to 0.4˚. In order to ensure that comparisons of $\Delta\Phi_{DP}(th)$ and $\Delta\Phi_{DP}(obs)$ were made well above these noise levels, we required that the rain path was at least 15 km long and yielded at least 10˚ of $\Delta\Phi_{DP}(obs)$. An upper limit of 12˚ was placed on $\Delta\Phi_{DP}(obs)$ so that measurements of Z_{DR} and Z_H (and thus $K_{DP}(th)$) were not significantly reduced by attenuation effects. In the mean, Z_H can be reduced by 1 dB when Φ_{DP} exceeds 14.5˚, and Z_{DR} loses 0.2 dB for Φ_{DP} values of 11.2˚. At C-band, large drops can produce differential phase shift on backscatter leading to transient maxima in $\Phi_{DP}(obs)$, and resonance effects can increase Z_{DR} (Bringi and Chandrasekar 2001). To avoid these difficulties, rays with large drops were thrown out if a single gate in the ray had Z_{DR} > 3.5 dB. Lastly, movie loops were examined and showed sudden, transient domain-wide decreases of Z_H as convection passed directly over the radar. The wetted radome thus attenuated Z_H without a noticeable increase in $\Phi_{DP}(obs)$. In order to avoid these scans, we computed the average Z_H at vertical incidence between altitudes of 840-2760 m which is beyond the antenna's near-field at 700 m. If the average Z_H at 90˚ elevation angle exceeded 20 dBZ, then the entire scan was discarded.

The presence of non-rain targets, such as ground clutter, anaprop, insects, hail, and partially melted snow in the melting layer impacted measurements of Z_H, Z_{DR}, $\rho_{HV}(0)$, $\Phi_{DP}(obs)$, and $\Phi_{DP}(th)$. A fuzzy logic algorithm for discriminating precipitating and non-precipitating echoes described in Gourley et al. (2006b) was used at each range gate. If > 5% of the bins along the rain path were classified as non-precipitating echoes, then the ray was rejected. Rays containing hail were rejected by requiring that all bins in the rain path had Z_H < 50 dBZ. Lastly, the range at which the 1.5˚ beam entered the melting layer was found by observing a decrease in $\rho_{HV}(0)$, an increase and fluctuation of Z_{DR}, and an increase in Z_H. Measurements in the melting layer were avoided by setting a maximum range for the rain path's end point to 65 km, but of course will need to be adapted for other radars and seasons. If a ray met all aforementioned criteria, then values for $\Delta\Phi_{DP}(obs)$ and $\Delta\Phi_{DP}(th)$ at the end of the rain path where 10˚ < $\Delta\Phi_{DP}(obs)$ < 12˚ were reported to file.

3 Calibration results

The French national weather service, MeteoFrance, has been operating a C-band polarimetric radar in simultaneous transmission and reception mode continuously since the summer of 2004. The transmitted pulses have a width of 2 μsec, a frequency of 5.64 GHz, a peak power of 250 kW, and a pulse repetition frequency of 379, 321, and 305 Hz. The 3-dB beamwidth of the 3.7m-diameter antenna is less than 1.1˚. Four hundred eighty-four scans of data at an elevation angle of 1.5˚ on 23, 26, 28, and 30 Jun 2005, 04 Jul 2005, and 10 Sep 2005 were used in the calibration experiment. Because the resolution of the polar data files are 0.5˚ in azimuth by 240 m in range, a total of 348,480 rays were examined. Of this total, only 1.5% of the rays (~5280) met all criteria discussed in the previous section. Figure 2 shows mean values of $\Delta\Phi_{DP}(th)$-$\Delta\Phi_{DP}(obs)x100/\Delta\Phi_{DP}(obs)$ for each scan, the standard error, and mean calibration (in % and dB) for each of the six days studied. While significant variability in calibration was noted from ray-to-ray, daily averages varied with time by 8% (0.3 dB) up to the 10 Sep case. Suddenly, the apparent calibration of Z_H jumped 25% (1.0 dB) between 04 Jul and 10 Sep. On 18 Aug, the radar's waveguide was severely damaged and subsequently replaced. This required us to recalibrate Z_{DR}, which changed from being biased by -0.08 before the replacement to -0.45 dB. The proposed method also detected a significant change in the calibration of Z_H.

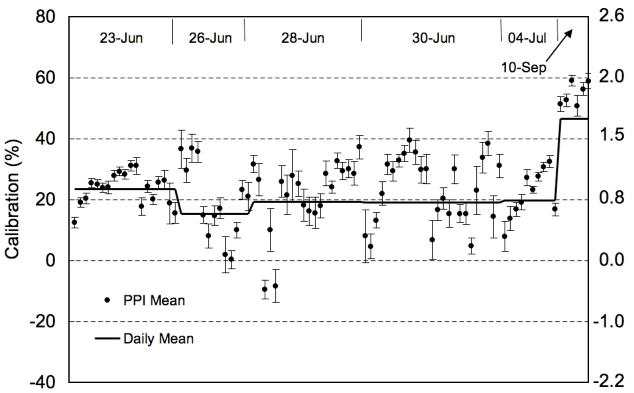

Fig. 2. Calibration of Z_H using consistency theory over time.

4 Sensitivity to raindrop shape model and inferences on their correctness

The same calibration experiment shown in Fig. 2 was carried out with commonly used raindrop shape models (Prupppacher and Beard 1970; Goddard et al. 1994b; Andsager et al. 1999; Brandes et al. 2002; Matrosov et al. 2005). We also evaluated a hybrid drop shape model that is essentially the same as Andsager for 0 < D_e < 1.5 mm and then Goddard for larger drops. Ideally, we'd like to examine the calibration results as a function of D_e. If the calibration bias depends on D_e, then there is evidence suggesting the drop oblateness to diameter relation is not entirely accurate. As an alternative, we calculated the ratio of $\Phi_{DP}(th)$ caused by Z_{DR} > 1 dB to Z_{DR} < 1 dB. We refer to this parameter as the Z_{DR} ratio hereafter. A Z_{DR} ratio of five indicates most of the $\Phi_{DP}(th)$ resulted from Z_{DR} > 1 dB. In this case, relatively large diameter drops were in the path. Smaller Z_{DR} ratios resulted from the presence of relatively small drops in the path.

Figure 3 shows the calibration results for the different drop shape models plotted as a function of Z_{DR} ratio. The linear models from Matrosov et al. (2005) and Pruppacher and Beard (1970) both show large, negative slopes of lines fitted to the calibration as a function of Z_{DR} ratio. This result indicates that the simple linear models are unsatisfactory with small drops that are too oblate and/or large drops that are too spherical. Goddard shapes produced a positive slope especially at Z_{DR} ratio < 1 indicating drops with diameters < 1.5 mm are too spherical. Of the nonlinear models, Andsager/Goddard and Brandes yielded the smallest slopes of -1.8 and -2.0 respectively. These two models were virtually indistinguishable from our analysis. In the mean, the apparent calibration between these two models differed by 8% (0.3 dB), which represents the expected precision of our proposed Z_H calibration method.

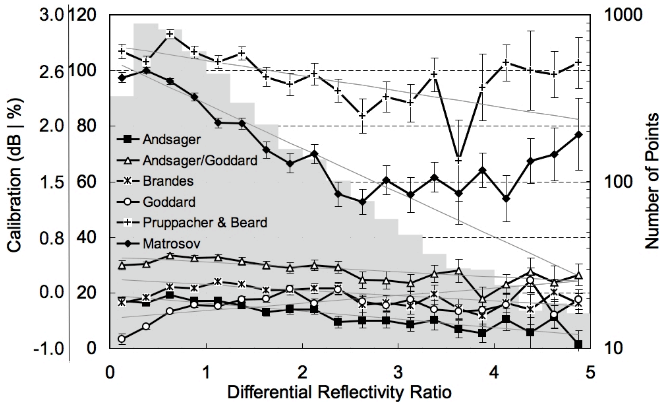

Fig. 3. Sensitivity of calibration of Z_H to raindrop shape model as a function of the ratio of the number of gates along the path with Z_{DR} > 1 dB to the number with Z_{DR} < 1 dB.

5 Conclusions

A polarimetric method that relies on the consistency between Z_H, Z_{DR}, and K_{DP} was described in this study to calibrate Z_H. Over the period of six days more than 5000 rays were analysed. Prior to 18 Aug 2005, the Trappes radar was calibrated by a hardware link budget, and our method indicated Z_H from the Trappes radar was still miscalibrated by 20% (0.8 dB). Following the waveguide replacement, the calibration suddenly jumped up to 46% (1.6 dB). We also examined the sensitivity of results to different raindrop shape models. As it turns out, this exercise illuminated the correctness of the models themselves. Linear models yield drop shapes that are too oblate at small drop diameter. This result questions the accuracy of rainfall rate retrievals and attenuation correction schemes that assume drop axis ratios decrease linearly with drop diameter. On the other hand, Goddard shapes yield small drops (< 1.5 mm) that are too spherical. Andsager/Goddard and Brandes shapes were virtually indistinguishable and the difference in the resulting calibration of 8% (0.3 dB) represents the uncertainty of our method.

6 References

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