9R.5 CALIBRATION OF ABSOLUTE REFLECTIVITY AT C-BAND USING REDUNDANCY OF THE POLARIZATION PARAMETERS IN RAIN

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1. INTRODUCTION

Recent studies in polarimetric rainfall estimation have shown improvements through the incorporation of Z_H, Z_{DR}, and K_{DP} measurements in a blended or synthetic approach (Ryzhkov et al. 2005). While K_{DP} is insensitive to radar calibration errors, analyses must be carried out to ensure Z_H and Z_{DR} are well calibrated. Polarimetric methods have been shown to independently calibrate Z_{DR} within 0.1 dB using precipitation at vertical incidence and reception from solar radiation. The precision of Z_H calibration may be the limiting factor in the accuracy of rain rates.

The absolute calibration of Z_H for an operational radar network presents a longstanding challenge in radar meteorology. Prior to the advent of polarization diverse radars, radars were typically calibrated through measurements from targets with known scattering properties, injecting known signal strengths to the receiver, comparisons with rain gauge accumulations, disdrometer measurements, and comparisons with reflectivity from neighboring radars. Another option is to capitalize on the redundancy between Z_H, Z_{DR}, and K_{DP} in rain. According to this consistency principle, K_{DP} can be estimated provided radar measurements of Z_H and Z_{DR}. Differences between computed and observed K_{DP} are then attributed to calibration errors in Z_H.

There are different approaches to formulating the redundancy relationship. A multiple linear regression analysis may be implemented which relies on three coefficients that relate the variables. Several different values for these coefficients exist in the literature, which are based on disdrometer-measured or modeled drop size distributions (DSD) and raindrop axial ratio to equivolume diameter (shape) relationships. Another approach is based on the assumption that the ratio of K_{DP} to Z_H is a well-defined function of Z_{DR} (Goddard et al. 1994; Illingworth and Blackman 2002). Moreover, this function is said to be virtually independent of DSD variability. Provided this assumption is valid, the calibration of Z_H can be evaluated for different raindrop shape models.

This study presents an analysis of observations collected by the Trappes C-band polarimetric radar to determine a) the extent to which accurate and consistent calibration of Z_H can be accomplished using the K_{DP}/Z_H vs. Z_{DR} approach, and b) the sensitivity of the results to differing raindrop shape models. Automated procedures have been developed to integrate and compare large data sets of computed and observed K_{DP}. Lastly, insights are provided regarding the validity of using the consistency relationships for retrieving the slope parameter in the linear raindrop shape model.

2. METHODOLOGY

a. Dependence on raindrop shape model

The first step in the automated polarimetric calibration methodology is the calculation of K_{DP}. Given observations of Z_H and Z_{DR}, K_{DP} is simply "looked-up" using the three curves in Fig. 1. The different curves represent three common models employed for relating drop axial ratios to their diameters. The simplest model is provided by Pruppacher and Pitter (1971). A linear dependence is assumed for raindrop diameters > 0.5 mm, otherwise they are assumed to be spherical. Goddard et al. (1995) proposed a new drop shape model that is based upon empirical adjustments to the linear shapes for drops > 1.1 mm. Beard and Chuang (1987) drops are quite similar to the Goddard shapes, yet were obtained by assuming the drops are at equilibrium in a steady air flow. Each curve assumes the DSD is a normalized gamma distribution with $\mu=5$, where curves produced with $\mu=0$ are nearly identical.

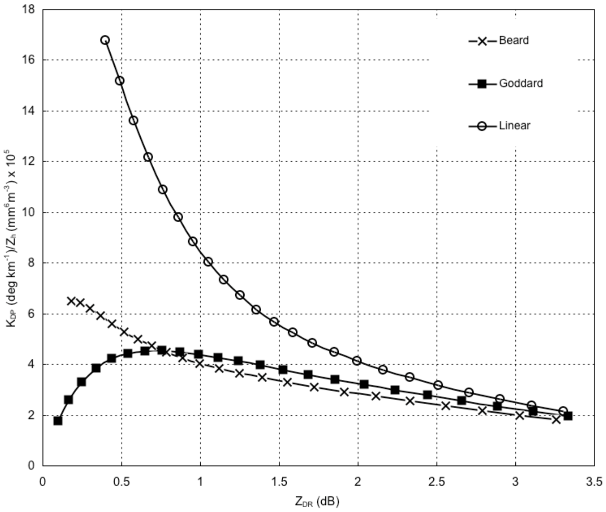

FIG. 1. Calibration curves for calculating K_{DP} given observations of Z_H and Z_{DR}. The different curves correspond to raindrop shape models of Beard and Chuang (1987), Goddard et al. (1995) and Pruppacher and Pitter (1971).

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After K_{DP} is estimated for each raindrop shape model, it is integrated in the radial direction yielding a computed value of Φ_{DP}.

b. Data quality of observed Z_{DR} and Φ_{DP}

Development of procedures to precisely calibrate Z_H highlighted several artifacts in observations of Z_{DR} and Φ_{DP} that may have otherwise gone unnoticed. First, it was observed that the apparent calibration of Z_H had a rather complicated, yet repeatable, dependence on azimuth angle. Observations of both Z_{DR} and Φ_{DP} were found to be azimuthally dependent for different reasons. A 1.6-m electrical box and 1-m tall perimeter fence on top of the radar tower were found to induce biases up to 0.4 dB in Z_{DR}. The waveguide rotary joint was discovered to be responsible for a sinusoidal dependence of Φ_{DP} on azimuth. Moreover, initial values of Φ_{DP} were biased low up to 6˚. Empirical filtering methods were devised to correct for these biases as reported in Gourley et al. (2005). Finally, Z_{DR} was absolutely calibrated using reception from solar radiation and measurements in precipitation at vertical incidence. It is imperative that these data quality checks are carried out in order to calibrate Z_H using redundancy theory.

c. Matching profiles of computed and observed Φ_{DP}

Calculated values of Φ_{DP} must be compared to observations of Φ_{DP}. Raw observations of Φ_{DP} have been found to have a system fluctuation of 1.8˚ (Gourley et al. 2005), thus necessitating the use of a 25-gate smoothing window where one gate is 240m long. Several criteria were imposed prior to matching and comparing profiles of estimated and observed Φ_{DP}. First, this study is dealing with observations of stratiform and convective rainfall at C-band in mid-latitudes. Attenuation effects at this frequency can either be corrected for, or they can be neglected by limiting the dataset to observations with small values of Φ_{DP}. While attenuation correction methods are believed to mitigate biases in observations of Z_H and Z_{DR}, uncertainties remain due to the estimation of attenuation being dependent on raindrop temperatures and Z_{DR}. The addition of uncertainty in observed Z_{DR} due to attenuation effects was deemed to be too significant for precise calibration of Z_H, so we have chosen to limit our dataset to observations of $\Phi_{DP} < 10˚$.

The calibration curves presented in Fig. 1 are valid for raindrops alone. Common scatterers that break down the redundancy theory are echoes from fixed targets, hailstones, and melting hydrometeors. Ground clutter was often noted to induce noisy and occasionally biased observations of Φ_{DP}. For this reason, profiles that had observed $\Phi_{DP} > 3˚$ within ranges of 10 km were discarded. Profiles containing hail had simultaneous high values of Z_H and low values of Z_{DR}. In order to avoid hail, profiles were discarded if an observation of $Z_H > 50$ dBZ was discovered anywhere along the path. The melting layer was avoided by requiring that the path-integrated $\rho_{HV}(0)$ had at least 95% of its values > 0.95.

Candidate profiles of computed Φ_{DP} were then smoothed along the same 25-gate window as observed Φ_{DP} so that they can be compared at the same spatial scales. Finally, the difference between estimated and observed Φ_{DP} is reported for the first range gate where $\rho_{HV}(0)$ is > 0.97 and observed Φ_{DP} is greater than 5˚, but less than 10˚. These latter criteria ensured that there was a statistically significant differential phase shift, yet not too large to be biased by attenuation effects. Observations of individual profiles revealed that these criteria permitted the dataset to include both stratiform and convective rain events.

3. RESULTS

a. No perturbation in observed Z_H

Significant rain events from May through July of 2005 were considered in this analysis. Over 2000 profiles met the criteria discussed in section 2. The initial state of Z_H calibration is evaluated without perturbing the observations of Z_H. Fig. 2 shows Φ_{DP} computed by the consistency relationship minus observations of Φ_{DP} for the three different raindrop shape models. The linear drop shape model yields estimations of Φ_{DP} that are much greater than the other two models. The average difference of consistency minus observed Φ_{DP} using this model is 4.6˚ with a rather large degree of uncertainty (i.e. standard deviation is 2.9˚). The Beard and Goddard models produce very similar results to one another with average differences of –1.3˚ and –1.1˚ respectively. The larger estimates using the Goddard model come from the slight offset in the curves at moderate Z_{DR} seen in Fig. 1. The standard deviations of the differences are substantially lower with these models at 1.1˚.

From this analysis, it appears as though the selection of raindrop shape model dictates the apparent sign and degree of miscalibration in Z_H. The use of the linear shapes in the consistency method yields differential phase shifts that are unrealistically high.

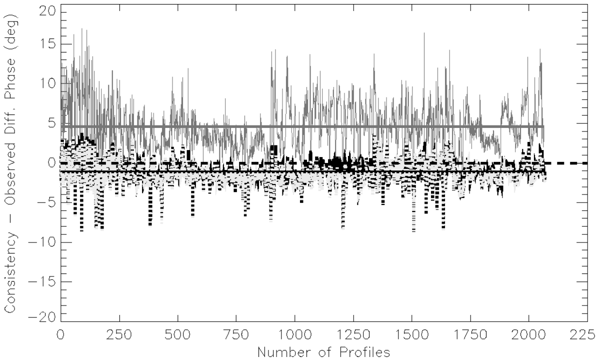

FIG. 2. The difference between Φ_{DP} estimated from consistency relations assuming the Beard (in black), Goddard (in light gray), and linear (in gray) drop shape models. Average differences for each model are shown as solid, horizontal lines.

Radar-rain gauge comparisons and radar-radar reflectivity differences have been conducted operationally on the Trappes radar over a 5-month duration and show no consistent, significant biases in Z_H (Gourley et al. 2005). The Beard and Goddard raindrop models, on the other hand, give consistency-based Φ_{DP} values that are much closer to observations. Section 3b explores the relationship between biases in consistency and observed Φ_{DP} versus biases in Z_H.

The trends of the curves using the Beard and Goddard shapes have random fluctuations of 1.1˚, but are steady state over the 3-month analysis period. Significant changes in the behavior of the apparent calibration Z_H would either cast doubt on the validity of the calibration curves in Fig. 1 being independent of DSD or suggest the raindrop size-shape relationships are evolving with time. However, this behavior is not observed which suggests that the consistency approach to calibration of Z_H is valid and the Beard and Goddard raindrop size-shape relationships suffice for Z_H calibration purposes. These initial conclusions are for observations collected at mid-latitudes at C-band frequencies.

b. 1 dB perturbation in observed Z_H

Prior studies at S-band indicate that a significant differential phase shift is required in order to adequately calibrate Z_H using the consistency method. A 1 dB perturbation in Z_H was introduced in order to determine the sensitivity of the consistency theory for small values of Φ_{DP}. Fig. 3 reveals that this perturbation results in increases of computed Φ_{DP} of approximately 2.5˚dB^{-1} (50%) for the linear model and 1.2˚dB^{-1} (25%) for both Beard and Goddard raindrop shape models. This sensitivity is sufficient for calibrating Z_H even with small differential phase shifts where attenuation effects can be ignored. Moreover, the perturbation in Z_H leads to excellent agreement between observed and consistency-derived Φ_{DP} values using either the Beard or Goddard shapes. The redundancy of the polarization parameters in rain suggest Z_H is miscalibrated by –1 dB.

4. CONCLUSIONS

This study examines the absolute calibration of Z_H using the consistency between Z_H, Z_{DR}, and K_{DP}. The approach undertaken assumes that relationship between K_{DP}/Z_H vs. Z_{DR} is independent of DSD variability. Consistency relationships are formulated for over 2000 profiles of polarimetric observations collected at C-band for three different raindrop shape models. The differential phase shifts computed with the linear drops are anomalously large and have much greater fluctuations. The magnitude of these phase excursions casts doubt on the validity of the linear raindrop shape model. The use of the Beard and Goddard models, on the other hand, produce differential phase values that are more consistent with radar-rain gauge and radar-radar reflectivity comparisons. A sensitivity test was performed and indicates that the redundancy method can be performed with small differential phase shifts (< 10˚) where attenuation effects can be neglected at C-band. A 1 dB perturbation results in a computed differential phase change of 25% using either the Beard or Goddard shape models. It must be noted, however, that care must be exercised in order to ensure that Z_{DR} is absolutely calibrated and neither Z_{DR} nor Φ_{DP} have azimuthal dependencies due to structures near the radome or due to the waveguide rotary joint. Results obtained for spatially and temporally integrated K_{DP} comparisons indicate that Trappes Z_H is miscalibrated by –1 dB.

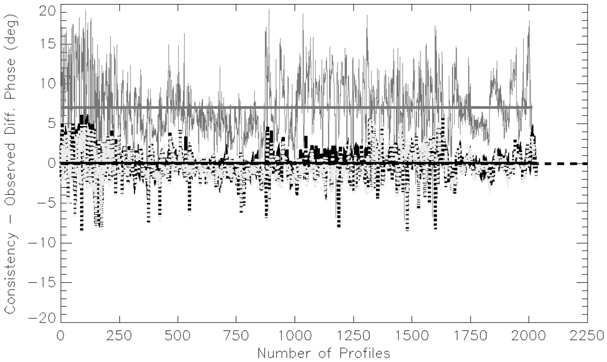

FIG. 3. Same as in Fig. 2, but with a 1 dB perturbation introduced to observations of Z_H.

The trends of the biases using the Beard and Goddard shapes reveal a steady state behavior with time. These observations suggest a) the consistency between the variables is valid for naturally varying DSD and b) the raindrop size-shape relationships do not change significantly with time. Based on our polarimetric observations at C-band in mid-latitudes, there is little evidence to support the notion that the linear raindrop shape model is valid or that the slope parameter is changing with time and needs to be retrieved.

5. ACKNOWLEDGEMENTS

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