P13.9 **DUAL-POLARIMETRIC RADAR APPLICATIONS AT KWAJALEIN ATOLL, RMI**

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1. INTRODUCTION

Dual-polarimetric (DP) ground-based weather radars are well recognized as vital instruments for applications in hydrology, precipitation microphysics, and hydrometeor identification (Ryzhkov and Zrnic 1998a, Vivekanandan et al. 1999, Straka et al. 2000, Gorgucci et al. 2001, Wang and Carey. 2005, among others); all of which provide unquestionable benefit to activities focusing on ground validation of satellite measurements (Chandrasekar et al. 2008).

Kwajalein, Republic of the Marshall Islands (KWAJ) (8.7°N, 167.7°E) is an ideal tropical oceanic location for which ground validation, mesoscale characterization, diurnal cycle studies, and other activities have focused (Schumacher and Houze 2000, Wolff et al. 2005, Yuter et al. 2005, Pippitt et al. 2009). In support of U.S. Army and Tropical Rainfall Measuring Mission (TRMM) Ground Validation (GV) operations at KWAJ, an S-band DP radar (KPOL) operates on a continual basis, providing unique opportunities for operational algorithm development and adaptation with applications clearly extendable to the Global Precipitation Measurement (GPM) GV program. KPOL is currently one of the only full-time (24/7) operational S-band dual-polarimetric (DP) radars in the tropics. Through the use of KPOL DP fields and disdrometer data from Kwajalein, the Precipitation Office at NASA's Goddard Space Flight Center (GSFC) has developed and adapted applications for quality control (QC), absolute reflectivity calibration, and rainfall estimation to be applied in a near real-time operational environment. While the methodology for development of such applications is well documented, tuning of specific algorithms to the particular regime and observed drop size distributions requires a comprehensive testing and adjustment period to ensure high quality products. Data studies in light rain/drizzle show that KPOL DP measurements (from 2006 and later) meet or exceed quality thresholds for these applications as determined by consensus of the radar community. Presented are algorithm descriptions and results from five case studies at Kwajalein in which QC, absolute reflectivity calibration, and rain rate estimation were performed. Also described is a unique approach to calibrate the differential reflectivity field when vertically oriented scans are not available. Results show the following: 1) DP-based QC provides superior results to the legacy Tropical Rainfall Measuring Mission (TRMM) QC algorithm, 2) absolute reflectivity calibration can be performed using observations of light rain at Kwajalein via a published integration technique, 3) calibration results are within ± 1 dB as compared to independent measurements, 4) multi-parameter DP-based area-averaged rain rate estimates are less than those obtained from the Probability Matching Method or a disdrometer-based Z-R, however the correlations with rain gauge data are somewhat higher, and 5) application of a polarimetrically-tuned Z-R shows remarkable agreement with independent rain gauge measurements.

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2. QUALITY CONTROL

KPOL reflectivity and DP data are frequently contaminated by ground and sea clutter, multiple-trip echo, and considerable noise. QC algorithms based on DP measurements have shown notable success in objective identification of these and other non-precipitation features (Ryzhkov and Zrnic 1998b, Zrnic and Ryzhkov 1999, Cifelli et al. 2002). A series of five KPOL case studies from 2006 through 2008, including the entire month of July 2008 were selected to develop an operational QC algorithm for detection and removal of non-precipitation echo. In our DP QC algorithm, a new data field with label "CZ" is created in each volume scan and contains the final pre-calibrated reflectivity that has been edited for non-precipitation echo. Initially, the CZ field is simply copied from the raw reflectivity field (ZT) for all elevations scans within a volume. As gates are identified as non-precipitation echo, they are assigned a specific value corresponding to the no-data flag. The initial step in the QC process is automated and applied by the RVP8 processor. A signal-to-noise ratio (SNR) test is applied to the total differential phase (Φ_{DP}), specific differential phase (K_{DP}), differential reflectivity (Z_{DR}), and cross-correlation (ρ_{HV}) fields to identify gates with weak or uncertain signals, and sets the value of these gates to the no-data flag. Multiple-trip echo is usually removed from the Φ_{DP} and ρ_{HV} fields by this technique; however, additional QC is required for multiple-trip in both Z_H (reflectivity, horizontal component) and Z_{DR} fields. All gates containing the no-data flag in the Φ_{DP}, ρ_{HV}, K_{DP}, and Z_{DR} fields are mapped to the corresponding gates in the QC'd reflectivity field CZ. This step takes advantage of the relatively clean Φ_{DP} and ρ_{HV} fields, and eliminates those gates from CZ that have been flagged with low SNR by the RVP8 processor. This step also removes gates from CZ for which there are no corresponding DP measurements.

The calculation of the standard deviation of differential phse [$\sigma(\Phi_{DP})$] at each range location, and subsequent threshold comparison, is shown in Ryzhkov and Zrnic (1998) to be a successful test for detection of anomalous propagation (AP)-induced ground clutter echo. Before computing the standard deviation, the Φ_{DP} field is de-aliased. Although AP of this type is not commonly observed in KPOL data due to the tropical oceanic location, it is certainly a serious problem for accurate rainfall measurements in regions affected by frontal boundaries and density gradients (Moszkowicz et al 1994, Pamment and Conway 1998). However, in the interest of portability to other sites, this test has been applied to KPOL data and has been found to be very effective in identification of ground clutter associated with human-made structures (i.e. buildings and towers). Using a running centered 15-gate sample, $\sigma(\Phi_{DP})$ is computed at each range gate. If at least five of the 15 gates contain valid Φ_{DP} measurements, their standard deviation value is assigned to the center of the radial interval; otherwise the σ value is set to the no-data flag. The requirement of five or more phase samples for a standard deviation calculation eliminates isolated gate speckle-type noise. When $\sigma(\Phi_{DP})$ calculations are complete for a given sweep, each gate value is checked against an established threshold of 12° (Ryzhkov and Zrnic 1998b).

Sea clutter, ground clutter from structures, and general noise are detected and eliminated by using a combination of $\sigma(\Phi_{DP})$ and ρ_{HV} thresholding. If a $\sigma(\Phi_{DP})$ gate is greater than the threshold, or has been set to the no-data flag, the corresponding CZ gate is set to the no-data flag. Similarly with ρ_{HV}, if a correlation gate is less than the threshold of 0.80, the corresponding CZ gate is set to the no-data flag. Analysis of ρ_{HV} within sea clutter reveals values mostly less than 0.40; however values in the range from 0.0 to near 0.95 can occur. A similar analysis of $\sigma(\Phi_{DP})$ within sea clutter shows standard deviation values ranging from 3° to 70°. With a ρ_{HV} threshold of 0.80, and a $\sigma(\Phi_{DP})$ threshold of 12°, almost all sea clutter is detected. Echo clearly identified as ground clutter displays typical ρ_{HV} values in the 0.4 to 0.95 range. More than 50% of these ground targets have ρ_{HV} values exceeding 0.80, and could easily be incorrectly identified as precipitation echo if the correlation test was considered alone, therefore, the $\sigma(\Phi_{DP})$ test is also needed. Within ground clutter, $\sigma(\Phi_{DP})$ has values ranging from 10° to near 80°, with a clear majority of values greater than 40°. The combination of the correlation and standard deviation tests identifies almost all ground clutter gates; however a small percentage of problem gates are not flagged by either threshold and survive the QC tests.

Figure 1 shows typical results of the QC algorithm for the Z_H field. The top panels (a,b) of Figure 1 show raw and corrected reflectivity images within 50 km radius and indicate the effective identification of ground clutter along the atoll perimeter (both embedded and non-embedded) in precipitation echo. It is clear that sea clutter, multiple-trip echo, and general noise have also been identified and removed. The bottom panels (c,d) of Figure 1 show a full 160 km 0.4° sweep before and after QC. Pronounced regions of multiple-trip echo (from 220 deg to 250 deg) have been removed in addition to widespread light noise.

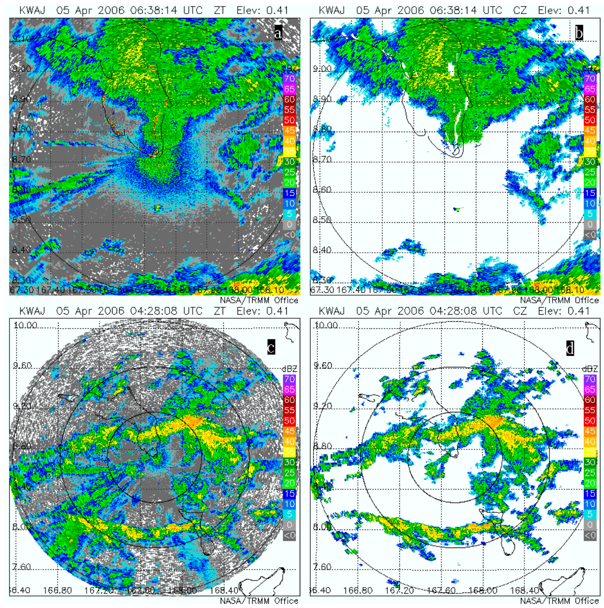

Figure 1. Results from application of the dual-polarimetric QC algorithm at Kwajalein.

A quantitative analysis of ground clutter returns reveals that DP QC results are superior to the legacy TRMM GVS (Ground Validation System non-polarimetric) algorithm. As discussed in Kulie et al. (1999), the GVS QC algorithm identifies non-precipitation echo by use of height and reflectivity threshold parameters, and has a significant weakness in removal of high-reflectivity ground clutter, especially when the clutter is near or embedded within precipitation. The strongest precipitation echoes at Kwajalein approach 50 dBZ, but ground clutter returns easily exceed this value with measurements ranging from 55 to 70 dBZ. Figure 2 shows the location of the clutter field at Kwajalein, with 1323 gates (within 50 km of KPOL) identified as frequent sources of clutter (Silberstein et al. 2008). Reflectivity gates are extracted exclusively from these locations from unedited (raw), and corrected data from both DP and GVS QC algorithms for the five daily case studies. To be reasonably certain that no precipitation echo is selected, only reflectivity values ≥ 55 dBZ are considered to be ground clutter. A case study from 19 Dec 2006 shows that 71 gates from a total of 11907 extracted gates have values ≥ 55 dBZ. DP QC has correctly identified and removed all 71 gates (100% correction), therefore zero clutter gates remain. GVS QC has 53 remaining clutter gates ≥ 55 dBZ, roughly corresponding to a 25% correction. Similar results occur for all cases. DP QC has virtually no clutter gates remaining, while GVS QC has significant numbers of clutter gates remaining. In all cases, precipitation echo is widespread and covers the entire field, and the ground clutter echo is mostly embedded in precipitation echo. The DP QC tests (correlation and standard deviation of phase) detect and remove the embedded clutter, but GVS QC historically fails in this regard. In cases with partial precipitation coverage and non-embedded clutter, it is possible for marginal improvement of GVS QC performance through threshold strengthening, but requires repetitive labor intensive processing. In contrast, the DP QC algorithm is fully automated and provides consistent results without the requirement of parameter adjustments.

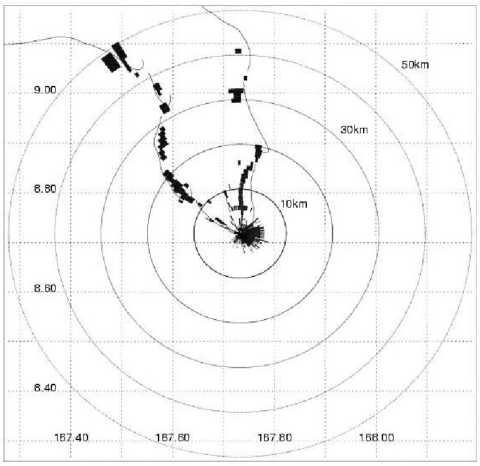

Figure 2. Clutter field at Kwajalein denoted by black areas surrounding the atoll edges.

3. Z_{DR} CALIBRATION

Accurate Z_{DR} calibration is essential in the determination of absolute reflectivity calibration via consistency among the polarimetric variables. The use of vertically pointing (or birdbath) scans in light rain is a favored and reliable approach to determine Z_{DR} bias (Gorgucci et al 1999, Hubbert et al 2008). The KPOL dataset from years 2006 and 2007 does not contain reliable birdbath scans; therefore an alternative calibration method was needed. The calibration of KPOL Z_{DR} was accomplished through bias adjustment to a disdrometer-based reference profile. Over 10 000 impact type JW (Joss and Waldvogel 1967) disdrometer observations of Z_H and Z_{DR} at KWAJ from 2003 and 2004 were compiled for the reference profile. Assumptions regarding drop size and shape relations used in the disdrometer Z_{DR} computation are discussed in Section 5. Before determining the proper Z_{DR} offset, the KPOL Z_H distributions were independently calibrated by the Relative Calibration Adjustment (RCA) method (Silberstein et al. 2008 – discussed in section 4). KPOL Z_{DR} data were then calibrated for individual rain events by application of specific offsets as determined by comparison to the disdrometer reference. The Z_{DR} Z_H disdrometer reference profile is shown in Figure 3a (bold line with no-symbols) together with profiles from five case studies in 2006 and 2007. The cases were chosen based upon rainfall coverage, and include those with uniform rain shields containing small embedded convective cells. The level of disagreement in Z_{DR} distributions within the cases is evident, and their bias relative to the disdrometer reference is shown.

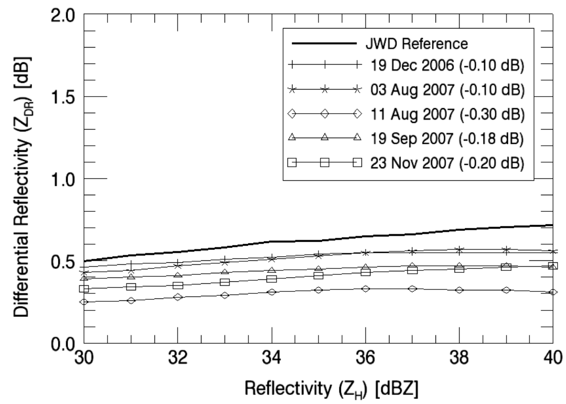

Figure 3a. ZDR profiles from five case studies compared to the reference disdrometer profile. Bias amounts are shown in the legend.

Figure 3b shows the Z_{DR} distributions after adjustment to the reference. Emphasis was placed on matching within the 30-40 dBZ range as this represents approximately 85-90% of the measurements used in self-consistency calibration.

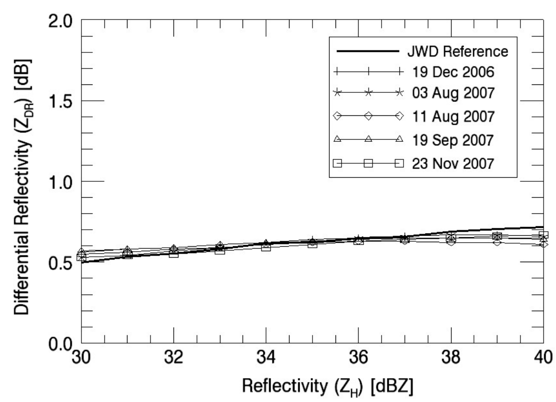

Figure 3b. Bias-adjusted KPOL ZDR profiles compared to the reference disdrometer profile.

While the adjusted Z_{DR} profiles are not in perfect agreement, and fluctuations due to sample size limitations are noticeable especially in the upper reflectivity bins, our analysis indicates that the agreement is sufficient to perform a robust calibration of Z_H using the self-consistency technique.

4. Z_H CALIBRATION VIA SELF-CONSISTENCY

Absolute radar calibration is a requirement for quantitative rainfall estimation (Ulbrich and Lee 1999). A calibration offset of 2-dB can result in rainfall estimation error of 30% as measured by the default WSR-88D reflectivity rain rate relationship ($Z=300R^{1.4}$). It is well documented that polarimetric properties of the rain medium (Z_H, Z_{DR}, and K_{DP}) can be used to determine the absolute calibration of a radar system. Techniques to capitalize on these consistency relations range from the comparison of rainfall rates derived from power and phase measurements (Gorgucci et al. 1992), to comparing observed and estimated differential propagation phase (Goddard et al. 1994, Vivekanandan et al. 2003, Ryzhkov et al. 2005, and others). The majority of these self-consistency calibration techniques have a common necessity of moderate to heavy rain rates (> 50 mm h^{-1}) for significant phase accumulation over the range profile. Ryzhkov et al. (2005) developed consistency relationships based on existing statistics of DSD measurements and polarimetric radar observations in central Oklahoma, and suggested a methodology for determining absolute reflectivity bias (Z_{BIAS}) from the self-consistency relation that did not require heavy rainfall. This methodology compared area-time integrals of measured (processor or user determined) K_{DP} and computed (theoretical) K_{DP} (as a function of Z_H and Z_{DR}) and determined Z_{BIAS} as the adjustment in Z_H needed for the integrals to agree.

The precipitation at Kwajalein is dominated by systems that form in the inter-tropical convergence zone (ITCZ), and shallow (< 5 km) "warm rain" clouds (Schumacher and Houze 2000, Wolff et al 2005) and is ideal for this self-consistency calibration application. To apply the area-integration methodology to KPOL data, DSD measurements from the Kwajalein region were required to derive a consistency equation between Z_H, Z_{DR}, and K_{DP}. Using simulated DSD, Vivekanandan et al. (2003), for example, derived a relationship where K_{DP} is expressed as a function of Z_H and Z_{DR}. In this study, we derived a similar relation using actual disdrometer observations. A JW disdrometer sited at Kwajalein from May through December 2003 provided 8779 1-minute resolution DSD measurements (within the 30-48 dBZ interval) to regress the following relation between the variables,

$$K_{DP} = A Z_H^b Zdr^c \quad (1)$$

(where A = 0.17737×10^{-4}; b=0.9926, and c = -0.5138) with Z_H in mm^6m^{-3}, Z_{DR} in dB, and K_{DP} in deg km^{-1}. The coefficient and exponents were derived via a linear least-squares fit regression.

In Ryzhkov et al (2005), their derived consistency equation from DSDs in Oklahoma reduced the impact of variability in the DSD and raindrop shape on the calibration results due to the large-scale integration technique. Following their method, we matched measured K_{DP} and computed $K_{DP}(Z_H, Z_{DR})$ by adjusting Z_H by an amount (in dB) considered as the Z_{BIAS}. A practical approach to accomplish this is to divide the data collected from an entire spatial/temporal domain into 1-dB increments of radar reflectivity and compute average values of $K_{DP}(Z)$ and $Z_{DR}(Z)$ in each 1-dB interval of *Z* between Z_{min}(30 dBZ) and Z_{max}(48 dBZ). The Z_{BIAS} is then determined by matching the integrals

$$I_1 = \int_{Z_{min}}^{Z_{max}} \overline{K_{DP}(Z)}\, n(Z) dZ \quad (2)$$

and

$$I_2 = A \int_{Z_{min}}^{Z_{max}} Z_H^b \overline{Z_{DR}}^c n(Z) dz \quad (3)$$

with an estimated Z_{BIAS} determined from Vivekanandan et al. (2003) by

$$Z_{BIAS}(dB) = 10 \log\left(\frac{I_2}{I_1}\right) \quad (4)$$

An iterative adjustment approach is required to force agreement of the integrals to within an established bound of 0.1 dB. In all cases analyzed, this has been accomplished with two or less iterations. The same cases analyzed for QC and Z_{DR} calibration were examined for self-consistency calibration.

As a basis for comparison and evaluation, the self-consistency results are compared against those from the independent RCA technique (Silberstein et al. 2008). The RCA uses a statistical ensemble of reflectivity values from persistent ground clutter areas from every volume scan to monitor hourly and daily radar sensitivity changes relative to an established baseline. As detailed in Silberstein et al. (2008), the 95^{th} percentile of the clutter area reflectivity distribution at the lowest elevation scan is remarkably stable to within ± 0.5 dB, and therefore permits monitoring of radar stability. Although the RCA provides a relative calibration, corrected KPOL reflectivity matched the PR to within ± 1 dB on a monthly basis (Marks et al. 2009). Table 1 shows self-consistency calibration results as compared to the RCA approach and the absolute value of their difference. From the case studies analyzed, there is agreement between self-consistency and RCA to within ±1 dB. In four cases, the agreement is within 0.5 dB. This is similar to the level of agreement found by Ryzhkov et al (2005), Illingworth and Blackman (2002), and Vivekanandan et al. (2003), upon comparison of corrected reflectivity with independent measurements. The KPOL results are consistent with previous calibration studies, and provide confidence in the operational method. As explained in Silberstein et al. (2008), there is ± 0.5 dB uncertainty in RCA measurements. Together with the possible ±1 dB uncertainty shown here, there is a combined calibration uncertainty of ± 1.5 dB.

Case mm/dd/yy	K_{DP} samples	Z_{BIAS} (dB)	RCA (dB)	|Diff| (dB)
12/19/06	5.46E+05	-2.44	-1.95	0.49
08/03/07	1.52E+06	-2.06	-1.78	0.28
08/11/07	3.36E+05	-1.46	-1.91	0.45
09/19/07	4.00E+05	-0.93	-1.91	0.98
11/23/07	7.41E+05	-2.17	-2.46	0.29

Table 1. Calibration results from five case studies. The self-consistency (Z_{BIAS}) result is compared to an independent statistical calibration method (RCA). Comparisons are within 1-dB.

5. RAINFALL ESTIMATION

Many researchers (Bringi et al. 1982; Chandrasekar et al. 1993; Carey and Rutledge 2000; Cifelli et al. 2002, and numerous others) have used multi-parameter algorithms for rainfall estimation. Chandrasekar et al. (1993) conclusively showed that the accuracy of these rainfall estimators changes with the mean rainfall rate being considered; therefore a single optimal algorithm for all rainfall rates is not possible. Such radar-based estimates of rainfall, referred to as "hybrid" techniques, are optimized when multi-parameter algorithms use combinations of: 1) ZH-only; 2) ZH and ZDR; 3) ZDR and KDP, or 4) KDP-only, depending on measured magnitudes of the DP variables. The resultant relationships are expressed as power laws, with exponents and coefficients estimated using representative DSD information, often obtained from disdrometer estimates.

The measurements of raindrop size distribution (DSD) that were collected from May through December 2003 with the JW disdrometer at Kwajalein Island were used to determine the polarimetric multi-parameter radar based rainfall relations. The rain rate, R, and polarimetric radar parameters of Z_H, Z_{DR}, and K_{DP}, were calculated for each minute of DSD observations for an S-band radar (10.7 cm) and a temperature of 20 ˚C as shown in Tokay et al. (2002). For drop shape, the mean axis ratios offered by Andsager et al. (1999) were adopted for drops less than 4 mm in diameter and equilibrium drop shapes (Beard and Chuang 1987) for larger drops. For the fall velocity, we adopted the terminal fall velocity drop diameter relation given by Beard (1976). The polarimetric radar rainfall relations were then derived through linear least squares and are given as follows:

$$R = 0.0264\, Z_H^{0.682} \quad (5)$$

$$R = 54.24\, K_{DP}^{0.795} \quad (6)$$

$$R = 0.00167\, Z_H^{0.962}\, Z_{DR}^{-0.912} \quad (7)$$

$$R = 62.52\, K_{DP}^{0.978}\, Z_{DR}^{-0.562} \quad (8)$$

where Z_H is in $mm^6\ m^{-3}$, Z_{DR} is in dB, and K_{DP} is in deg. km^{-1}.

The relations derived here may represent open ocean climate and differ substantially from the relations that were derived for other climate regions. Cifelli et al. (2002), for instance, employed $R(K_{DP})$, $R(Z_H, Z_{DR})$ and $R(K_{DP}, Z_{DR})$ relations of Bringi and Chandrasekar (2001), and local disdrometer derived $R(Z_H)$ to estimate the rainfall in the Amazon region of Brazil. Applications of Cifelli et al. (2002) relations to the disdrometer observations in Kwajalein resulted in 11% difference in total rainfall than that based on the relations in equations (5) through (8). In the hybrid method, the choice of variables used to make the estimate is dependent on the observed magnitude of Z_H, Z_{DR} and K_{DP}. For the lightest rain rates, where the magnitudes of Z_{DR} and K_{DP} are low, a default Z-R (i.e Z_H only) is used. For this analysis, we chose two different default Z-Rs. The first is the PMM-based relationship currently used to develop the TRMM 2A-53 rain product (see Wolff et al. 2005). The second default Z-R was derived using JW disdrometer data observed over the period May-December 2003 (Eq. 5). It should be noted that given the relatively light rains observed at Kwajalein, these default Z-Rs are used for the majority of pixels; however, the contribution to the total areal rainfall is dominated by application of the Z_H+Z_{DR} estimate. Figure 4 shows the decision tree flowchart and thresholds used for the hybrid equation approach.

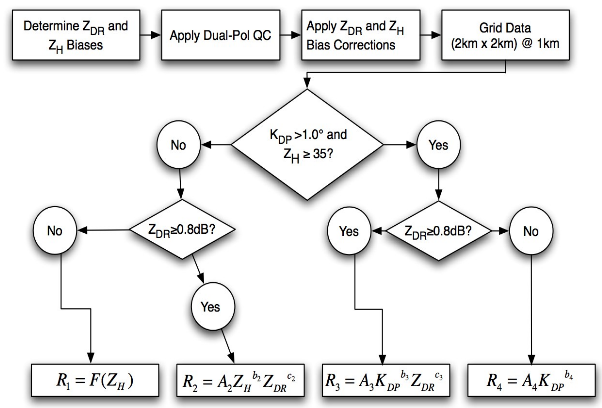

Figure 4. Decision tree and thresholds for the hybrid equation approach.

Figure 5 shows scatterplots of monthly rainfall accumulations for the period July-December 2008 at Kwajalein. The top left panel compares the PMM-only based radar estimates versus the gauge estimates. The top right panel shows a DSD-based (Eq. 5)-only radar estimates versus the gauge estimates. The bottom left panel shows the DP-hybrid technique, with PMM as the default Z-R, and the bottom right panel shows the DP-hybrid technique using Eq. 5 (DSD-based Z-R) as the default Z-R. As expected, the PMM-only estimates are well correlated (ρ=0.87) and unbiased (-0.7%) relative to the gauges; however, it is encouraging to see that the DSD-based Z-R also does quite well, with a bias of -3.4% and correlation of 0.88. Application of the hybrid technique actually shows higher correlations (ρ=0.92) for both the DP using PMM as the default Z-R, and DP using Eq. 5 as the default Z-R, although they are both negatively biased (-19.7% and -19.9% for the DP+PMM and DP+DSD, respectively).

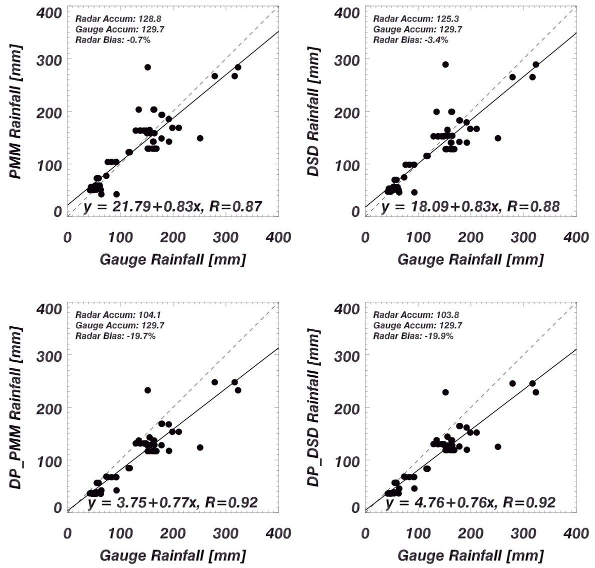

Figure 5. Comparison of different rain rate estimation techniques for July-December 2008.

Another method to estimate rain rate was proposed by Bringi et al. (2004) and is referred to as the polarimetrically-tuned Z-R approach (PTZR). They begin with the assumption of a first-guess Z-R relationship of the form:

$$Z=aR^{1.5} \quad (9).$$

The coefficient in (9) is then continuously adjusted as the DSD evolves in space and time. This method assumes a normalized gamma DSD (Testud et al. 2001), with shape paramter (μ), median drop diameter (D_0), and concentration (N_w) obtained via S-band polarimetric measurements in varying rain rate conditions (Gorgucci et al. 2002). We note that the new coefficient in (9) is calculated at each pixel, and the application of the PTZR to a given pixel is dynamically determined by the magnitude of observed Z_H, Z_{DR}, and K_{DP}. This technique has shown very encouraging results at Kwajalein. For example, after application of the PTZR to a several months of KPOL data (July-December 2008), the resultant radar accumulations showed excellent agreement with fully independent rain gauges, with a bias of -14.8% and a correlation of 0.96 (see Figure 6). Although the DP-based biases are low, relative to the PMM-only and the DSD-only Z-R approaches, the higher correlations show that calibration of the gauges and/or the radar data might improve these results. What is especially encouraging is the fact that the PTZR approach provides such consistent results without the need of collecting gauge data; a time consuming and costly effort. Gauge data are absolutely necessary for validation of results, but in a regime such as Kwajalein with limited locations for gauge sites, and logistically difficult maintenance and data collection, the PTZR approach can provide high quality near-real-time radar rain estimates.

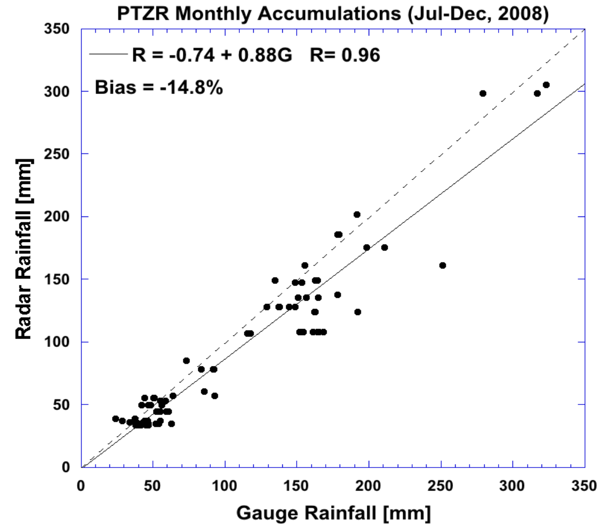

Figure 6. Scatterplot of gauge and radar monthly accumulations for July-December 2008 at Kwajalein using the PTZR approach of Bringi et al. (2004).

6. SUMMARY

DP radars are a vital tool for GPM validation due to their applications to rainfall microphysical retrievals. The ability to provide consistent and long-term calibrated ground-based DP measurements will prove essential for calibration of the core GPM satellite and for development of physically based passive microwave radiometer algorithms over land. Through the retrieval of DSD parameters relating drop size and shape, rainfall estimation, and hydrometeor identification, the DP radar can provide validation of parameterized microphysical properties.

Presented are operational algorithms for QC, absolute reflectivity calibration, and rain rate estimation (tuned for the Kwajalein site) using polarimetric properties of the rain medium. Application of the QC algorithm has shown to be robust with superior results compared to the standard TRMM GV QC algorithm that employs height and reflectivity thresholds. The ability to detect and remove ground and sea clutter embedded in precipitation echo is a distinct advantage of the DP algorithm. Through application of thresholding tests for correlation and standard deviation of differential phase, almost all clutter-type returns are identified and removed. In contrast, the TRMM GV algorithm can remove ground clutter only when not embedded in precipitation, and can be a labor-intensive process. In addition, the RVP8 processor correctly identifies multiple-trip echo through an automated SNR power test; a successful result to which the QC algorithm takes full advantage.

A technique to determine Z_{DR} calibration through analysis of combined Z_{DR} Z_H profiles was developed and applied to KPOL data. This application relies on the independent RCA for reflectivity calibration, and adjusts Z_{DR} profiles to match a disdrometer distribution when birdbath scans are not available. By this technique, uncertainty has been mitigated in Z_{DR} data from significant rainfall events in 2006 and 2007 and has allowed application of self-consistency reflectivity calibration.

A self-consistency approach to determine absolute reflectivity calibration using properties of the rain medium in light rain has been tested with KPOL data from five case studies and found to provide good results (within ± 1.0 dB) as compared to the independent RCA method. The approach follows the work of Ryzhkov et al. (2005) where K_{DP} data from light rain events are integrated and compared against a model consistency equation derived from disdrometer data at Kwajalein. The results indicate that the method can be successfully applied to lighter precipitation regimes. The most consistent results were found in cases with uniform rain shields.

We employed two different DP-based rain rate estimates. The first used a hybrid approach where a given rain rate estimate is based on the magnitude of the observed DP variables (Z_H, Z_{DR} and K_{DP}). We also employed the polarimetrically-tuned Z-R approach of Bringi et al. (2004) which resulted in noticeably improved correlations and reduced bias with rain gauges as compared to the hybrid equation technique. This result is impressive considering that the Bringi approach does not require gauge data for calibration and is therefore able to provide high-quality radar rain products in near-real-time. It is suggested that in lighter rain regimes (such as the Kwajalein area), a polarimetrically-tuned Z-R approach provides the best use of polarimetric variables for rain rate estimation compared to methods using one polarimetric estimator or multiple hybrid equations.

7. REFERENCES

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