DUAL POLARIZATION QUANTITATIVE PRECIPITATION ESTIMATION ON THE WSR-88D: CURRENT STATUS AND FUTURE PLANS

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1. INTRODUCTION

Quantitative precipitation estimation (QPE) has been an important component of the NEXRAD program's mission and requirements ever since the NEXRAD Technical Requirements were first approved in 1981. Prior to the upgrade of the WSR-88D network to dual polarization (i.e., dual pol) in 2011, the operational precipitation product (Precipitation Processing System or PPS) was based on reflectivity (Z) through the use of various R(Z) relationships which were subsequently adjusted with rain gauge data to correct bias (Fulton et al. 1998). The PPS derived accumulation products are still routinely being generated as part of the suite of hydrometeorological products available from the WSR-88D's Open Radar Product Generation (ORPG) software.

With the dual pol upgrade to the WSR-88Ds came a suite of precipitation products in ORPG Build 12 that leveraged the new dual pol moments, including differential reflectivity (Z_{DR} for dB units, Z_{dr} for linear units), differential phase (Phi_{DP}), specific differential phase (K_{DP}), and cross-polar correlation coefficient (Rho_{HV}). The new products included the Digital Instantaneous Precipitation Rate (DPR), One-Hour Accumulation (OHA), Digital Accumulation Array (DAA), Storm Total Accumulation (PTA), Digital Storm Total Accumulation (DTA), Digital User-Selectable Accumulation (DU3/DU6), Digital One-Hour Difference (DOD), and the Digital Storm-Total Difference (DSD).

The purpose of this paper is to summarize the evolution of the dual pol precipitation products and algorithms over the years since they were first deployed and to present improvements to the algorithms that are both currently under development and are planned for future ORPG Builds. The algorithm changes will be described in the context of their impact to QPE performance and how that relates to practical applications by users.

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2. OPERATIONAL HISTORY OF DUAL POLARIZATION QPE

The NEXRAD's initial operational dual pol rain rate algorithm was based on the echo classification-based synthetic rain rate method described by Giangrande and Ryzhkov (2008), which was installed with ORPG Build 12 at all WSR-88D sites starting in March 2011. It assigned one of three different rain rate relationships based on input from: the Hydrometeor Classification Algorithm (HCA; Park et al. 2009); the Melting Layer Detection Algorithm (MLDA; Giangrande et al. 2008); base data and dual pol moments resampled to one degree azimuth by 250-meter range resolution; and reference data such as beam blockage maps, volume coverage pattern (VCP) metadata, and site-specific adaptable parameters. A concise overview of the NEXRAD's implementation of HCA, MLDA, and the dual pol QPE algorithms was presented by Berkowitz et al. (2013). The subsequent build releases after Build 12 included incremental tuning and improvements to the algorithms, and the updates most relevant to the dual pol QPE products are listed below.

2.1 *ORPG Build 13 (First Beta Site: May 2012)*

As the first major build released after the dual pol upgrade, ORPG Build 13's updates for dual pol QPE predominantly involved minor bug fixes, including improvements for better QPE performance in areas of anomalous propagation and partial beam blockage. Updates were made to the MLDA as well to provide better melting layer height calculations in tropical cyclones and where melting layers were within 1 km above radar level. Build 13 also included the operational implementation of Automatic Volume Scan Elevation

Termination, or AVSET, which allows volume scans to terminate early when minimal echoes are detected at higher tilts, resulting in faster volume scan times. The Supplemental Adaptive Intra-Volume Low-Level Scan (SAILS) functionality was added operationally in Build 13.1, which allowed users the option to repeat the lowest tilt in the VCP midway through the volume scan for faster low-level updates. However, many of the weather algorithms within the ORPG were not updated to support those extra scans until later builds, including QPE.

2.2 *ORPG Build 14 (First Beta Site: February 2014)*

Shortly after the earliest dual pol upgrades were installed, it became apparent that improvements were needed for QPE within the melting layer (Cocks et al. 2012; Berkowitz et al. 2013). In the dual pol rain rate algorithm, the $R(Z,Z_{dr})$ relationship is allowed up to the MLDA's defined threshold where the radar beam center reaches the bottom of the melting layer (Table 1, Fig. 1). At that threshold a sharp boundary exists beyond which only R(Z) is utilized with coefficients that are specific to each HCA ice category. There were often situations where the accumulations from $R(Z,Z_{dr})$ in the rain region were much lower than the R(Z)-based relationships in the melting layer, leading to a pronounced "ring" artifact in the accumulated precipitation products (Fig. 2).

In collaboration with several WFOs in Eastern Region, the ROC conducted a field test in 2014 to allow sites to set site-specific coefficients for the R(Z) relationships in the dual pol rain rate algorithm. Results of the field test from the participating offices were successful in reducing the overestimation bias in the melting layer, so the adjustable coefficients were implemented across the entire WSR-88D fleet with Build 14.

HCA Classes and Other Conditions (ORPG Build 18)	**Rain Rate**
Ground Clutter (GC) or Unknown (UK) or MetSignal<80% *(site adjustable)*	Not Computed
No Echo (ND) or Biological (BI)	0
Light/Moderate Rain (RA) or Big Drops (BD)	$R(Z,Z_{dr})$
Heavy Rain (HR) and blockage<20% and <=45dBZ	$R(Z,Z_{dr})$
Heavy Rain (HR) and blockage>=20% or Z > 45 dBZ	$R(K_{DP})$
Rain/Hail (HA) and blockage>=5%	$R(K_{DP})$
Rain/Hail (HA) and echo is at or below the top of the melting layer (ML) and blockage<5%	$R(K_{DP})$
Rain/Hail (HA) and echo is above the top of the ML and blockage<5%	0.8*R(Z)
Graupel (GR)	0.8*R(Z)
Wet Snow (WS)	0.6*R(Z)
Dry Snow (DS) and echo is at or below the top of the ML	R(Z)
Dry Snow (DS) and echo is above the top of the ML or Ice Crystals (IC)	2.8*R(Z) *(site adjustable)*

Table 1. NEXRAD Dual Pol Precipitation Rate classification method

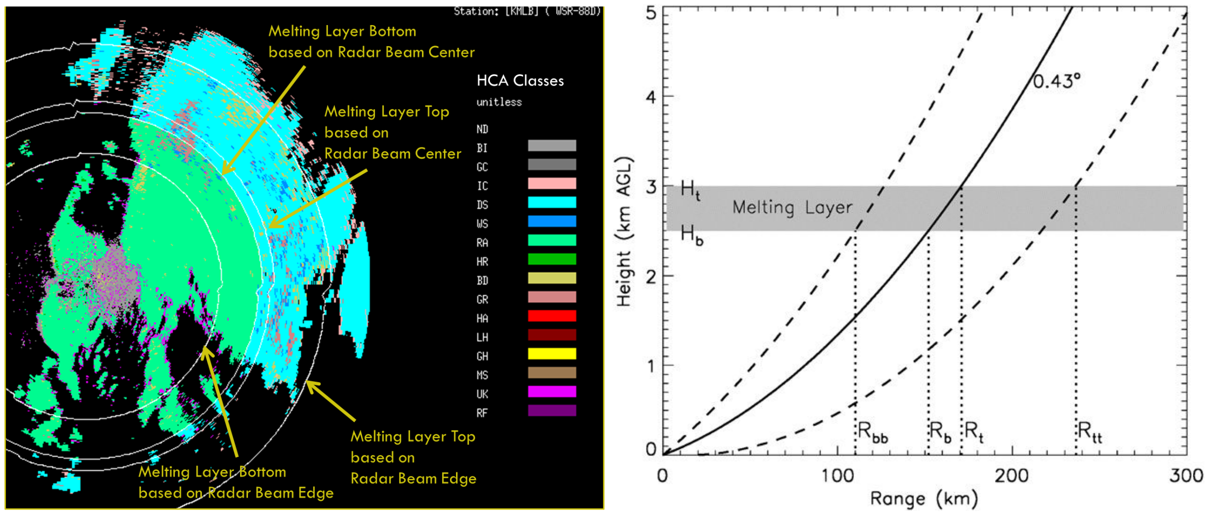

Figure 1. The dependence of HCA categories on radar bin location relative to the MLDA-defined melting layer boundaries (left), and MLDA threshold definitions based on beam edge and center height relative to the melting layer (right; from Park et al. 2009)

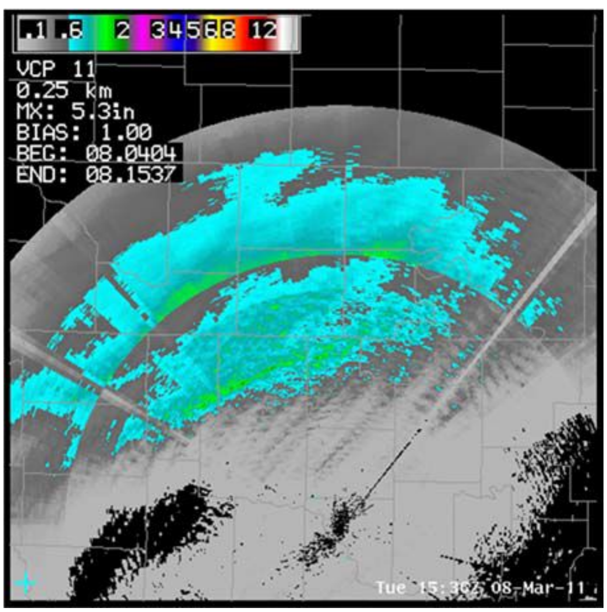

Figure 2. Sharp boundary observed in dual pol precipitation accumulation products where HCA classes transition from liquid to ice hydrometeor classification. (from Berkowitz et al. 2013)

2.3 *ORPG Build 15 (First Beta Site: February 2014)*

According to Table 1, the Dry Snow HCA class is assigned an R(Z) coefficient of 1.0 if the radar echo is below the top of the melting layer. If the radar echo is above the top of the melting layer, it is assigned an R(Z) coefficient of 2.8. The original implementation of the dual pol rain rate algorithm in Build 12 defined the “top” of the melting layer as the height at which the center of the radar beam exits the melting layer, whereas the original algorithm proposed by Giangrande et al. (2008) defined the top of the melting layer as where the entire radar beam was above it. As shown in Fig. 1, the slant range distance between the beam-center and beam-edge defined boundaries is significant and allowed for a large area of melting snow to use the higher 2.8*R(Z) relationship that was intended for pure snow. Once the threshold was corrected within the ORPG code in Build 15, the overestimation trend in the melting layer was largely resolved (Fig. 3).

Another important update in Build 15 was that users were given the option to select different $R(Z,Z_{dr})$ relationships. As an alternative to the “Tropical” $R(Z,Z_{dr})$ for rain that was deployed with the original algorithm, sites could also use a “Continental” $R(Z,Z_{dr})$ relationship that was better suited for continental convective storms (Giangrande et al. 2008).

2.4 *ORPG Build 16 (First Beta Site: March 2015)*

Compared to earlier build releases, Build 16 included relatively few updates for the dual pol QPE algorithms. The one-hour Digital Accumulation Array (DAA) product was updated to generate true “top-of-the-hour” accumulations whenever a new hour occurred during a volume scan in order to better align temporally with rain gauge observations. The

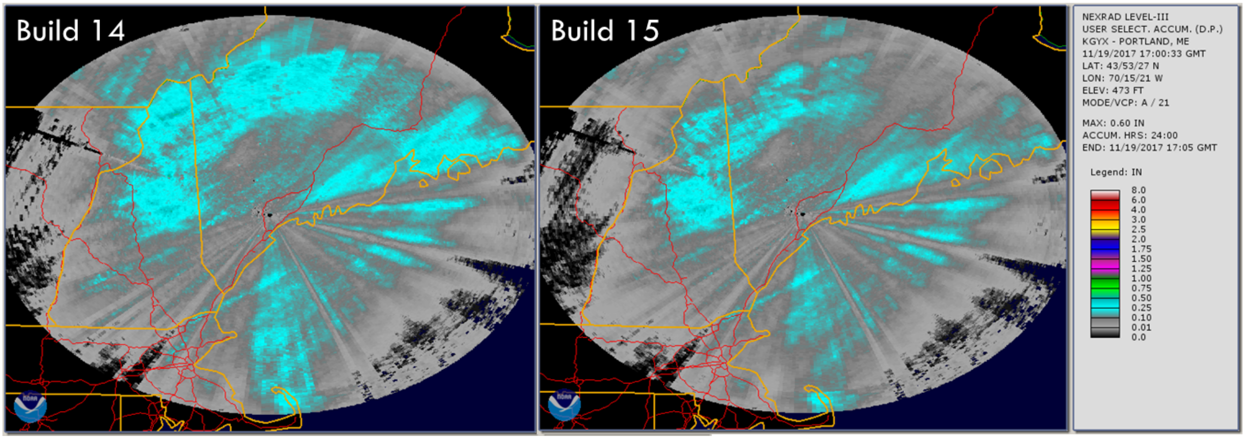

Figure 3. Change in dual pol QPE accumulations within the melting layer when the rain rate criteria for Dry Snow was updated to restrict the 2.8 coefficient to where the entire radar beam is above the melting layer.

instantaneous rain rate was changed from $R(Z,Z_{dr})$ to $R(K_{DP})$ where HCA classified "Heavy Rain" in areas of high reflectivity (i.e., Z>45 dBZ), and field sites were given the option to modify the maximum precipitation rate allowed from the default of 200 mm hr^{-1}.

2.5 *ORPG Build 17 (First Beta Site: April 2016)*

For dual pol QPE algorithms, Build 17 included an update to change the default $R(Z,Z_{dr})$ relationship from the originally deployed "Tropical" equation to the "Continental" equation, which tended to produce lower rain rates across the full range of precipitation intensities.

A new algorithm called MetSignal was added to the ORPG software in Build 17 that uses base and dual pol data to estimate the likelihood that each range gate contains predominantly hydrometeors. The primary purpose of MetSignal was to mask non-precipitation echoes out of K_{DP} and the dual pol precipitation products (Krause 2016). An investigation is currently underway to determine if additional products may benefit from such a QC process to remove non-precipitation returns, but no changes to existing products have been approved for a future build at this time.

Build 17 also included the operational deployment of the Multiple Elevation Scan Option for SAILS, also known as MESO-SAILS, which allows field sites to add up to three extra scans of the lowest elevation angle to their VCPs. However, the dual pol QPE products were not updated at the time to use the more frequent updates.

2.6 *ORPG Build 18 (First Beta Site: January 2018)*

Build 18 included relatively few and more minor updates for the dual pol QPE algorithms compared to previous builds, but there were updates to the HCA that had an impact on dual pol rain rates within and above the melting layer. With the observation that HCA was too frequently classifying "Dry Snow", two separate changes were made to the fuzzy logic membership functions that would instead favor more classification of "Wet Snow" and correctly classify non-precipitation echoes (e.g., biota) that were previously not allowed above the freezing level. The impact of both changes on the dual pol QPE would be to reduce precipitation rates. Dry Snow is assigned a precipitation rate of either 1.0*R(Z) (within melting layer) or 2.8*R(Z) above the top of the melting layer, whereas Wet Snow gets a lower coefficient of 0.6*R(Z) as shown in Table 1. Furthermore, changing from a rain or snow class to the biota class would reduce the precip rate at that range gate to zero.

3. CURRENT ACTIVITIES

While the initially deployed dual pol QPE algorithm tended to exhibit a high precipitation bias particularly in the melting layer (Cocks et al. 2012), the series of changes made within the ORPG software that were described in Section 2 have culminated in a present day algorithm that exhibits a consistent low bias instead (Cocks et al. 2018). Figures 4a and 4b show performance of the Continental and Tropical $R(Z,Z_{dr})$ relationships relative to rain gauges for 24-hour accumulations from 39 events using the Build 18

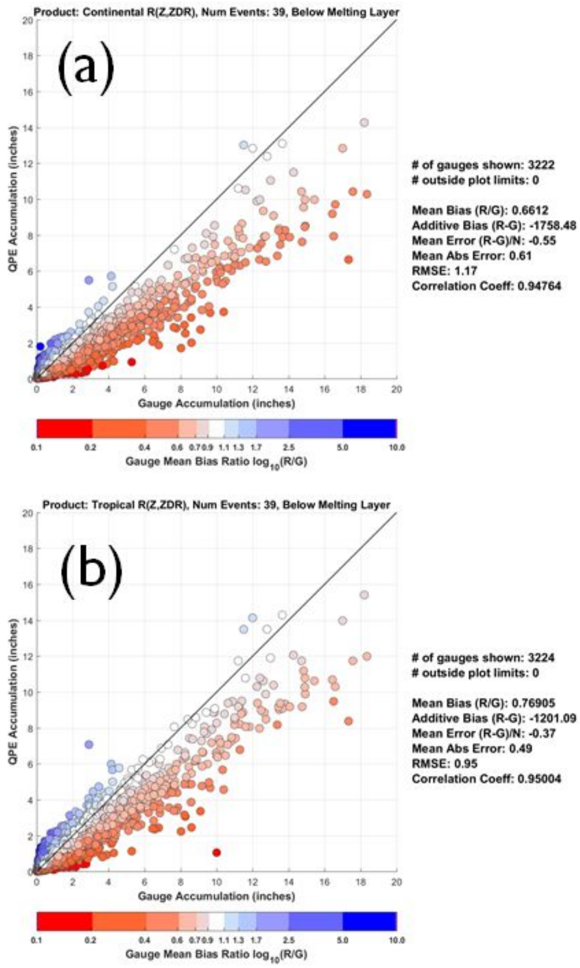

Figure 4. Scatterplots of 24-hour rainfall accumulations ending at 7am local time for 39 events. The y-axis represents the dual pol QPE accumulation total and the x-axis represents rain gauge accumulations from CoCoRaHS and quality-controlled MADIS automated gauges. Gauges shown represent observations from the nearest radar that were measured below the melting layer. Panel (a) shows QPE accumulations from the Continental R(Z,Z_{dr}) (ORPG default) and Panel (b) shows QPE accumulations from the Tropical R(Z,Z_{dr}).

software. Both options available to ORPG users tend to underestimate precipitation accumulations, with the bias worsening with increasing precipitation amounts. This “conditional” bias is problematic when considering that QPE accuracy is most critical in warning operations for the heaviest precipitation events where flash flood warnings and impact statements are based on rainfall intensity.

3.1 *ORPG Build 19 (Tentatively Early 2020)*

3.1.1 The Specific Attenuation Rain Rate Method

Build 19 will include an update to the dual pol rain rate algorithm that is expected to improve the underestimation bias currently observed in pure rain. The Specific Attenuation Rain Rate method (R(A); Ryzhkov et al. 2014) has been under development at the National Severe Storms Laboratory (NSSL) for several years and was mentioned as a candidate for implementation in the ORPG software as early as 2013 (Berkowitz et al. 2013). Continued development and improvements to the R(A) algorithm at NSSL have resulted in a robust rain rate method that performs well over a wide variety of rainfall types, seasons, and radar measurement challenges. It is a major component of the new Dual Pol QPE algorithm being deployed in MRMS with their Version 12 release and has been implemented in the ORPG software for Build 19. Three primary areas of QPE improvement are expected from R(A) over R(Z,Z_{dr}), which include automated adjustments for changing rainfall microphysics, reduced impacts from partial beam blockage (PBB), and insensitivity to Z_{DR} bias.

Historically with QPE algorithms in the ORPG software, the radar’s operator would need to manually select one of several R(Z) or R(Z,Z_{dr}) relationships for the specific type of precipitation event they were expecting due to the sensitivity of Z and Z_{DR} to varying drop size distributions. The dual pol QPE algorithm was initially deployed with only one R(Z,Z_{dr}) option, but a second was added in Build 15 when it became apparent that one relationship would not be sufficient after dual pol was deployed across the entire WSR-88D network. The calculation of R(A), however, more effectively leverages the microphysical signatures for rain that dual pol variables provide to adapt automatically to changing precipitation characteristics. Following the formulation described by Ryzhkov et al. (2014), as well as others cited therein, the attenuation parameter A is a function of both raw Z (no attenuation correction applied) and a parameter called path integrated attenuation (PIA), which can be estimated from the total change of Phi_{DP} down-radial as:

$$PIA = \alpha \Delta \Phi_{DP}$$

The parameter α represents the ratio of A to K_{DP} and can be sensitive to changes in the drop size distributions of rain. At S-Band, K_{DP} has limited sensitivity to very light precipitation and A can have large radial-to-radial variability (Ryzhkov et al. 2014), so the α parameter is instead optimized as a linear function of the "slope" of Z_{DR} along the reflectivity range typical for pure rain (20 to 50 dBZ):

$$\alpha = -0.75\frac{\Delta Z_{DR}}{\Delta Z} + 0.04875$$

The α parameter is estimated once per volume scan and can have a range from 0.015 for precipitation with more continental convective characteristics (i.e., high Z_{DR} at the upper range of Z, indicative of the presence of larger drops) to 0.04 for precipitation with tropical characteristics (i.e., relatively lower Z_{DR} at high Z, indicative of small drops). Using the slope of Z_{DR} as opposed to the direct measurement of Z_{DR} allows R(A) to be much less sensitive than $R(Z,Z_{dr})$ to large Z_{DR} biases introduced by miscalibration or hardware malfunctions in the radar. In stratiform rain where a large percentage of data points may fall below 30 dBZ (with many areas even below 20 dBZ), the 20-50 dBZ slope method is not as representative. Thus, α is set to a relatively high value of 0.035 to reflect the predominance of small drops in light stratiform rain. Alternatively, if a minimum number of data points is not available in a volume scan due to very sparse precipitation, α is set to a default value of 0.015 until more widespread precipitation is observed. Figure 5 shows the results of using R(A) below the melting layer in the ORPG software for the same 39 events evaluated in Figure 4.

Replacing $R(Z,Z_{dr})$, both Continental and Tropical, with R(A) in the dual pol QPE algorithm improves all the statistical measures of accuracy and bias that were computed (i.e., mean bias ratio, additive bias, mean error, mean absolute error, and root mean square error) as shown in the text to the right of each scatterplot in Figs. 4 and 5. Correlation coefficient was the only metric that did not improve with R(A) but was comparable to the other two rain rates tested. The reduced correlation with R(A) is due to a combination of factors, including an increase in noise observed in the rain rate field that is attributed to noisy Phi_{DP} in low rain rates and the inclusion of additional gauges with R(A) that were located in severely blocked sectors and were removed as outliers for the $R(Z,Z_{dr})$ statistics.

Along with automatically being able to adapt to varying precipitation types and an insensitivity to Z_{DR} bias, another major advantage of the R(A) is its insensitivity to partial beam blockage (PBB). In the 20+ years that have passed since all the radars in the WSR-88D

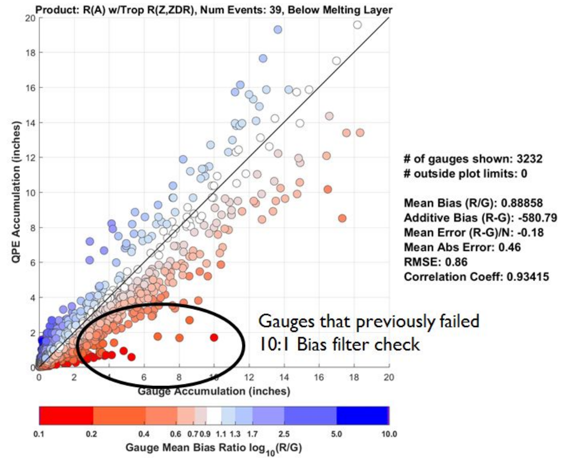

Figure 5. Same as Fig. 4 but using R(A) instead of $R(Z,Z_{dr})$. Points highlighted with the black circle represent gauges in blocked sectors that were excluded from the previous scatterplots as outliers.

network were originally installed, tree growth and construction of buildings and towers have introduced an ever-increasing number of blockages that are not reflected in the terrain-based blockage maps used to construct the hybrid scan and reflectivity corrections for QPE. While power-based variables like Z and Z_{DR} are sensitive to beam blockage, Phi_{DP} is immune, which is the primary reason why $R(K_{DP})$ is applied in the dual pol QPE algorithm for low percentages of partial beam blockage from terrain (Table 1). R(A) is also PhiDP based, and the impact of using R(A) vs. $R(Z,Z_{dr})$ for tree blockage is demonstrated in Figure 6. Since R(A) can only be used for pure rain and is not reliable for frozen precipitation, it will only improve QPE for PBB where the radar beam is below the bottom of the melting layer. However, where it can be used, the reduction in blockage impacts will be substantial.

3.1.2 Other ORPG Build 19 Updates

While the implementation of R(A) is expected to be the most significant change coming with Build 19, there are additional updates that will be of interest to users of the dual pol QPE products. Although SAILS and MESO-SAILS were implemented operationally in previous builds, the extra low-elevation scans have not been used in the dual pol QPE until Build 19. The temporal frequency of products will remain the same

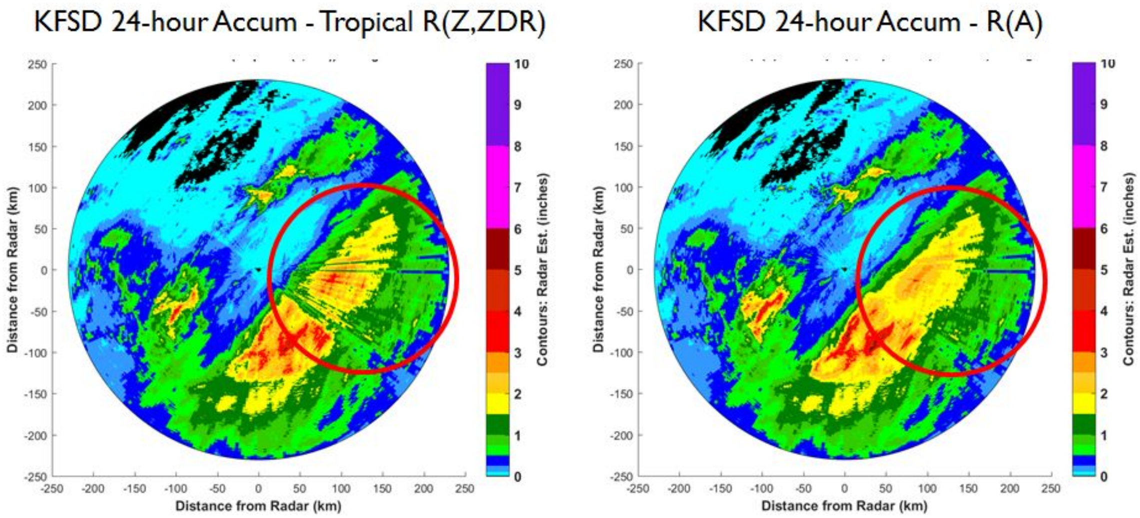

Figure 6. Impact of tree blockage at KFSD on 24-hour precipitation accumulations using both the Tropical R(Z,Z_{dr}) relationship (left) and R(A) (right). R(A) is applied only where the radar beam is below the bottom of the melting layer, so blocked radials look the same in both versions at the edge of the radar's range where R(Z) is used instead.

(i.e., one DPR product per volume scan), but the accumulation products will leverage the more frequent rain rate updates where the lowest angle was used in the hybrid scan. Higher tilts in the hybrid scan will still only update once per volume unless the Mid-volume Rescan of Low-level Elevations (MRLE) option is enabled, which is a Build 19 addition that can add up to four sequential low elevation scans in the middle of the volume scan (rather than repeating the lowest angle as in SAILS). Quantitatively, the addition of SAILS and MRLE scans do not tend to improve accuracy of the dual pol QPE, but qualitatively they do produce smoother, more continuous precipitation accumulations, particularly for fast-moving storms where "skipping" patterns in the QPE can appear as an artifact of the volume scan update times (Fig. 7).

A new R(K_{DP}) relationship is also being added in Build 19 that will be applied only where the HCA identifies the Rain/Hail mixture class and correlation coefficient is lower than 0.97. The new relationship has a lower multiplier (27 instead of 44) and its purpose is to mitigate a high rain rate bias that can occur due to very high K_{DP} in the vicinity of melting hail.

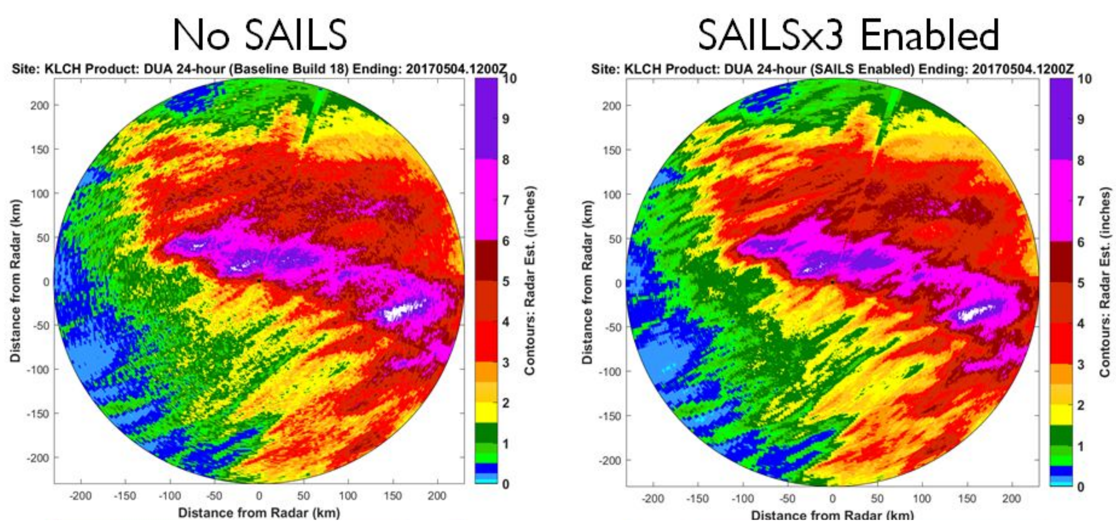

Figure 7. Impact of adding SAILS support to the dual pol QPE accumulation products for a 24-hour accumulation at KLCH (Lake Charles, LA).

4. FUTURE IMPROVEMENTS

ORPG Build 20 development efforts will focus on continuing improvements to R(A) for reducing noise in low rain rates and better α estimation, as well as the ongoing challenge of better quantifying precipitation where the radar beam intersects the melting layer. Figure 8 shows an exaggerated example of the "ring" artifacts than can occur at MLDA boundaries when there are large differences between the various rain rates used in the dual pol QPE. The innermost circle was computed using R(A), which is insensitive to Z_{DR} bias as already noted and can only be applied where the radar beam is traversing pure rain. The HCA allows rain to be classified up to where the center of the radar beam reaches the height of the bottom of the melting layer (white circle in Fig. 8), so $R(Z,Z_{dr})$ is still used in dual pol QPE for a small distance between the beam edge and beam center defined melting layer bottom. In the example shown in Fig. 8, Z_{DR} was biased 1.0 to 1.5 dB too low, which leads to a high bias in the $R(Z,Z_{dr})$ derived rain rate. Thus, a ring of high rain rates appear between the two rain rate relationships that do not depend directly on Z_{DR} (R(A) and R(Z)). As a side note, since the vast majority of radars across the WSR-88D network never see Z_{DR} bias that far out of tolerance (the recommended limit for accurate $R(Z,Z_{dr})$ is Z_{DR} +/- 0.2 dB), the discontinuities presented in Fig. 8 will rarely appear so extreme. In the R(Z) region of the domain, another artificial boundary appears where the beam edge clears the top of the melting layer, which is where the R(Z) multiplier for Dry Snow transitions from 1.0 to 2.8 (Table 1). The aim of future melting layer updates is to implement an approach that is not so closely tied to melting layer transitions, such as the VPR Correction approach described by Zhang and Qi (2010) as well as dual pol enhancements to the VPR Correction methodology that are currently under development.

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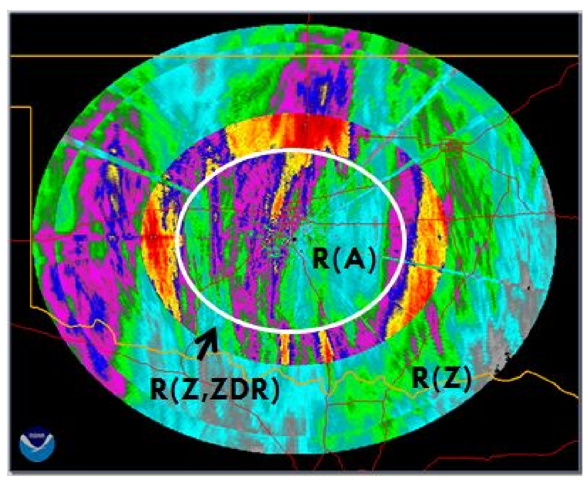

Figure 8. An example of artificial "ring" artifacts that can appear in the dual pol QPE algorithm at MLDA-defined melting layer boundaries, particularly when there are large errors in ZDR for a radar.