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IMPROVING THE QUALITY OF DUAL POLARIZATION ESTIMATES WITH MULTISCAN DATA HYBRIDIZATION

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Abstract

Altering the temporal separation between radar samples exercises the ambiguity tradeoff known as the Doppler dilemma. Relatively long pulse repetition times (PRTs) reduce the occurrence of range ambiguities, while short PRTs extend the Nyquist interval and reduce velocity ambiguities. The WSR-88D volume coverage patterns employ scans at lower (less than 7 degrees) elevation angles that make use of long and short PRTs. Split cut scans collect two, 360 degree scans with the first using the long PRT and the second using the short PRT. Batch mode scans collect both long and short PRT data within each radial for a single 360 degree scan. The purpose of employing both long and short PRTs is to obtain measurements that maximize the physical extent of the data collection and reduce the occurrence of velocity aliasing, respectively.

The recently added dual-polarization capabilities for WSR-88D radars produce estimates that are calculated using samples collected with both the long- and short-PRT scans in the split cut mode. While dual-polarization estimates do not benefit from the short PRT in the same way radial velocity does, a general improvement in the statistical accuracy and ground clutter filter performance is observed due to the increase in the number of samples. It is therefore advantageous to combine the measurements obtained over the range extent of the long PRT with the more accurate short PRT data. Given the range ambiguities associated with the short PRT, it is necessary to account for the possibility of overlaid echoes and the statistical deterioration that can occur in such cases. In this work, criteria for determining the appropriate power thresholds for use of the short PRT for combined split cut PPIs in the event of overlaid echoes are explored through the use of simulations. Results for a variety of meteorological scenarios are used to identify and evaluate appropriate thresholds. Recommendations stemming from and analysis of the simulation output will be presented, and it is anticipated that the use of the hybridization technique will improve the statistical properties of base moment data, and therefore improve WSR-88D dual-polarization data quality.

1. Introduction

Dual-polarization processing techniques have remained essentially the same since the recent upgrade of the WSR-88D network. Initial processing schemes were simple so as to avoid unnecessary complications during the first stages of operation. Since that time, large errors in the polarimetric variables have been observed, and efforts to remove or reduce the errors are being explored. One such technique is the use of multiple scans to provide enhanced statistical performance.

In general, estimates from time-series data collected with a short PRT, typically associated with a Doppler scan, exhibit better statistical performance than those from data collected with a long PRT, which is associated with a surveillance scan on operational VCPs. The validity of this assumption for specific VCPs will be explored further. One drawback of the use of the short PRT is the short unambiguous range, which causes susceptibility to overlaid echoes. Similar to the process that leads to the purple haze in radial velocity or spectrum width data, polarimetric variable data from range gates with overlaid echoes must be analyzed and sorted as valid or invalid.

Currently, the classification of valid and invalid data is performed by comparing the surveillance scan (long PRT) echo power at a particular trip of the short PRT (echo under test, EUT) with the sum of the echo powers at the other short-PRT trips. If the EUT power exceeds the sum of the other echo powers by a threshold, referred to as T_{over}, the meteorological variable estimates from the short-PRT scan are deemed valid and used in the downstream products. Otherwise, they are deemed invalid, and the data from the long-PRT scan for that particular gate are used. On the WSR-88D, T_{over} is an adaptation parameter arbitrarily chosen to achieve an operationally acceptable balance between data quality and obscuration. Whereas the value of this threshold is deemed acceptable for the Doppler variables, there is no evidence that suggests this is the case for the polarimetric variables. The goal of this work is to examine a variety of overlaid scenarios through simulation for each polarimetric variable, and determine the proper

T_{over} to provide more intelligent use of the short- and long-PRT data. The next sections provide an overview of the simulation methodology and the results of the analysis.

2. Simulation Methodology and Theory

Simulations have several advantages over collecting real data, but the main benefit is the ability to control the true characteristics of the underlying weather for both the EUT and overlaid echoes. This makes it significantly easier to obtain meaningful quantitative results. Another advantage is the ability to systematically study a wide range of cases. In this section, the basic structure of the simulation is described, along with the decision criteria for the selection of test cases.

The weather simulator utilizes a technique developed by Zrnić (1975), but expanded to include dual-polarimetric signals (Galati and Pavan 1995). The weather simulator produces dual-polarization time-series data based on the true values of all six meteorological variables (Z, v, σ_v, Z_{DR}, Φ_{DP}, ρ_{hv}). Weather signal simulations are commonly used to study the performance of algorithms before they are implemented on real systems. By adding two different weather signals together, the effects of the simulated overlaid scenario can be quantified directly. The algorithms that are used to process the data in the simulations are the same algorithms that are implemented on the WSR-88D radars. A block diagram of the overlaid echo simulator is presented in Figure 1, which will be referenced in the subsequent discussion.

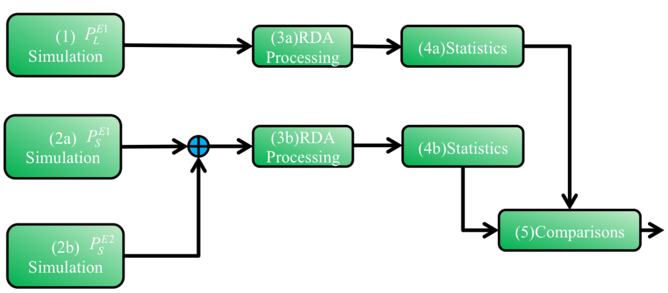

Figure 1: A block diagram of the overlaid echo simulator. Two separate weather echo time series are produced for the short-PRT scan, and are summed to produce the overlaid echo. The long-PRT time series are calculated separately and are used for statistical comparisons. The processing stage mimics that of the WSR-88D RDA.

Block 1, one of the weather signal simulations, takes the true values of the meteorological variables (Z, v, σ_v, Z_{DR}, Φ_{DP}, ρ_{hv}) as input as well as the number of samples (M), the noise power (N), and signal-to-noise ratio (SNR) associated with the EUT for the long PRT (T_{s1}). For the simulations and without loss of generality, the horizontal and vertical channel noise powers are assumed to be the same, and the SNR is relative to the horizontal channel. Two complex time series channels are produced at the output of Block 1 representing the horizontal- and vertical-channel data. For this study, 50,000 realizations are simulated to achieve accurate statistical results.

Block 2a and 2b generate the weather signals associated with the short PRT (T_{s2}) EUT and weak trip echoes, respectively. The two signals are related to one another through the overlaid power ratio, or OPR, which will be referred to in units of dB. For the purposes of this study, only two echoes are considered, which simplifies the analysis without loss of generality. Expansion to three or more echoes in future work will incorporate the basic techniques developed here for two echoes. The two short-PRT time-series signals are summed together to produce the range-overlaid data. The long-PRT time-series signal for the primary echo is left as-is for comparison.

Block 3 performs the traditional processing as implemented in the WSR-88D, which produces the spectral moments (Z, v, σ_v) and the polarimetric variables (Z_{DR}, Φ_{DP}, ρ_{hv}). In Block 4, the output of Block 3 is compared with the simulator input values, producing the performance metrics of the estimators: bias and standard deviation. The statistics of the overlaid short-PRT data and the long-PRT data are compared in Block 5, allowing for decision criteria to be developed.

To reduce the simulation time, the input values of the simulation were restricted to a subset of all possible values. Values of Z_{DR}, σ_v, and ρ_{hv}were chosen based on the likely range of valid meteorological returns as defined by the hydrometeor classification scheme presented in Park et al. (2009). Values of these parameters outside of said ranges would likely be classified as biological or clutter, and would not be included in downstream algorithms. Table 1 summarizes the input values. In total, simulations for 283,392 input combinations were used for each VCP case. Values of SNR were limited to those at or above the recently recommended censoring levels for the polarimetric variables, namely 10 dB for Z_{DR} and Φ_{DP}, and 15 dB for ρ_{hv}. The parameters of the EUT and overlaid echoes are denoted by superscripts E1 and E2, respectively. The OPR values are defined relative to the EUT power, and the overlaid echo power is held constant. Several volume coverage patterns (VCPs) were simulated to provide data and criteria that

Table 1: Input Value Parameters

Parameter	Values
Z_{DR}(E1, E2)	[-1 0 1 3] dB
ρ_{hv}(E1, E2)	[0.8 0.9 0.95 0.99]
σ_v(E1, E2)	[1 2 6] m s^{-1}
SNR (E2)	[10 15 20] dB
OPR (E1)	[0:140] dB

could be directly applied in an operational implementation. VCPs 11, 12, 21, 31, and 32 were simulated, however, VCP 11 is used to represent the simulation results and criteria selection methodology. VCP 12 was originally chosen to facilitate the discussion, however, as will be shown, VCP 12 does not exhibit the anticipated improvement with the use of estimates based on the short-PRT data. Similarly, VCP 31 short-PRT scans do not provide the necessary improvement over the long-PRT data, and will not be discussed.

3. Simulation Results

a. Assumption Validation

As mentioned before, meteorological-variable estimates from data collected using shorter PRTs are preferred in general due to clutter filter performance. Each of the operational VCPs under analysis uses split-cut scans at the lowest elevation angles. As such, both a surveillance and Doppler scan are available at each of the lower elevations. The simulation methodology described in the previous section was generated with the parameters specific to each VCP split-cut scan (PRT and number of samples), and the output was analyzed.

To examine the validity of the assumption that the data generated from the short-PRT scan exhibit better statistical performance than the long-PRT scan data, simulations were performed for each of the aforementioned VCPs. The number of samples was varied while other parameters were held fixed. The results indicate the minimum number of samples required for the short-PRT data to exhibit better statistical performance than the long-PRT data. As an example, the output of the simulator for VCP 11 and 12 and a specific set of input parameters is presented in Figure 2.

The dashed red line indicates the bias or standard deviation of the long-PRT data for the specific VCP, while the blue and magenta lines represent the response of the long- and short-PRT parameters, respectively, as the number of samples changes. The black 'X' indicates the actual number of samples used in the short-PRT scans, specific to the VCP scan. As shown, the VCP 12 short-PRT scan fails to outperform the long-PRT scan in this case. Similar results are observed for the other polarimetric variables and input parameters. VCP 31 displays similar behavior as well.

b. Radial Velocity Consideration

In the course of exploring the impact that various parameters have on the performance of the estimators, it was realized that the difference in radial velocity (Δv) between the overlaid and primary echoes can have an effect. Any difference between the echoes' mean radial velocity is interpreted as an increase in spectrum width, which may result in improved statistical performance if the other simulation parameters are fixed (Melnikov and Zrnic 2004). That is,

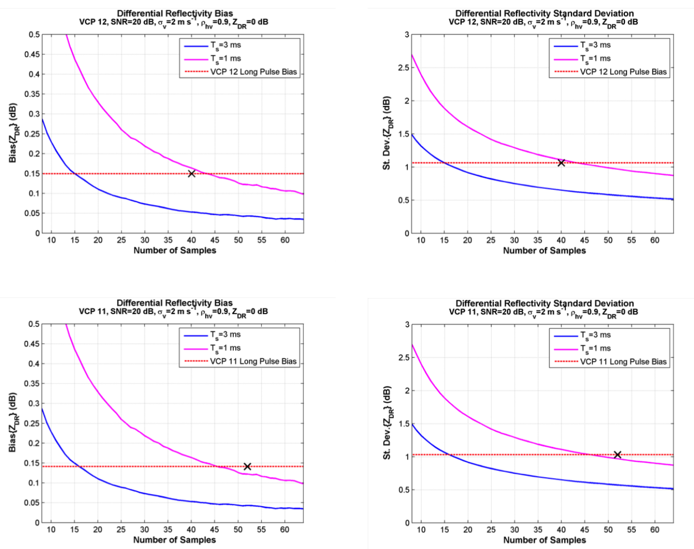

Figure 2: Bias and standard deviation results for VCP 11 and 12 Z_{DR} calculations as a function of sample size. The blue and magenta lines represent the response of the long- and short-PRT calculations, respectively. The dashed red line indicates the bias or standard deviation at the number of samples associated with the VCP surveillance scan. The black 'X' indicates the number of samples used in the Doppler scan. Note that the VCP 12 short-PRT scan does not outperform the long-PRT scan, while it does in VCP 11. Similar results are observed for different input parameters and Φ_{DP} and ρ_{hv} calculations.

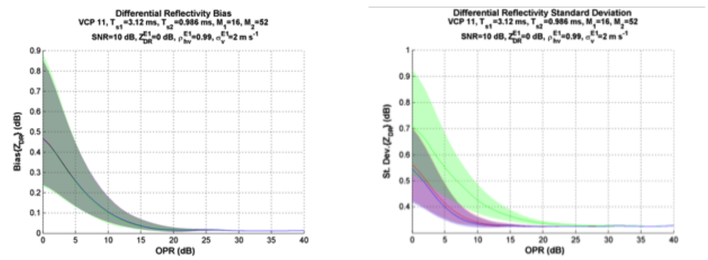

Figure 3: Statistical results for VCP 11 examined at three Δv values. Δv refers to the difference in mean radial velocity between the overlaid echo and EUT. The solid lines represent the median bias or standard deviation for a given set of parameters, and the shaded regions represent the interquartile range. The green, red, and blue colors refer to Δv values of 0, $v_{\mathrm{a}}/2$, and v_{a}, respectively.

an overlaid echo with the same EUT simulation parameters, but with a shifted Doppler velocity, will exhibit an improvement in statistical performance when compared with an overlaid echo with collocated Doppler velocity. Results for the Z_{DR} variable for three values of Δv are presented in Figure 3.

Each of the plots illustrates the median bias or standard deviation by the solid colored line, and the interquartile range by the transparent shaded region of the same color. The median and interquartile range statistics are generated from a fixed EUT (shown in the figure title) and the full suite of overlaid echo parameters. Biases are presented as absolute values. Green, red, and blue represent Δv values of 0, $v_{\mathrm{a}}/2$, and v_{a}, respectively. The Z_{DR} bias is not influenced significantly by Δv, however, the standard deviation is. As Δv increases, the standard deviation decreases, making the Δv=0m s^{-1} representative of the worst case. Similar results are observed with the Φ_{DP} and ρ_{hv} estimates. All subsequent simulations will use equivalent velocity inputs for the overlaid and primary echoes to preserve the worst-case assumption and thereby eliminating the need to include Δv in the simulation parameters.

c. *Results*

The exploration of cases in which the overlaid echo does not have the same parameters as the EUT is straightforward. For each set of EUT parameters, the performance of the short-PRT polarimetric-variable estimators can be examined for the full suite of overlaid echo parameters. This results in 48 curves for each EUT, which are compared to that of the single long-PRT estimates. The results for all simulated overlaid-echo parameters for VCP 11 Z_{DR} and a particular set of EUT parameters are presented in Figure 4.

The blue line and shading represent the median and in-

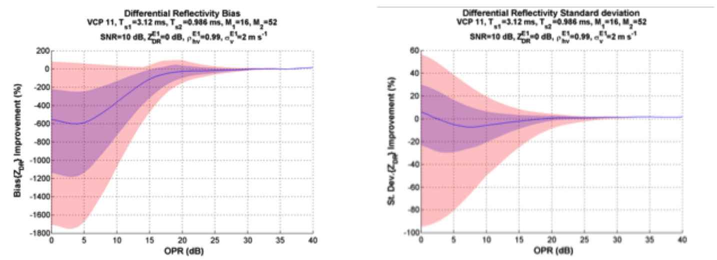

Figure 4: Percent improvement of the short-PRT Z_{DR} bias and standard deviation calculations over the long-PRT for VCP 11. The solid blue line represents the median improvement, while the blue shaded region represents the interquartile range. The red shaded region delineates the maximum range of values. Negative values are indicative of a degradation in performance. The improvement at high OPR values is 7% and 1.5% for Z_{DR} bias and standard deviation, respectively.

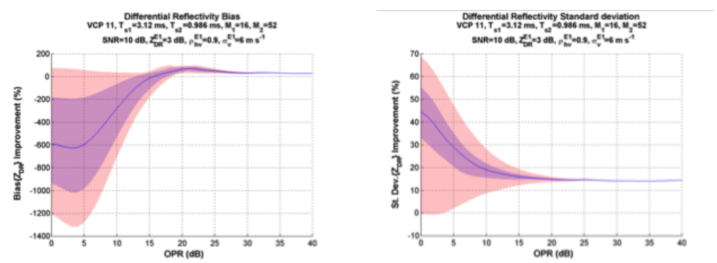

Figure 5: As in Figure 4, except for a different set of EUT parameters. Both the bias and standard deviation of the Z_{DR} estimate exhibit significant improvement at high OPR values (51% and 15%, respectively). Similar results are observed with Φ_{DP} and ρ_{hv}.

terquartile range of short-PRT estimate biases or standard deviations as percentages of the corresponding statistics for the long-PRT estimates. The red shading represents the normalized minimum and maximum deviations. In general, the illustration captures the poor performance of the short-PRT estimators at low OPR values. Of importance is the improvement that can be obtained at the higher OPR values, which will be quantified later in a table.

The images presented in Figure 4 represent a case in which the improvement obtained by using short-PRT estimates is minor. Another set of illustrations produced by using slightly different EUT parameters is presented in Figure 5. In this case, the potential for improvement in the estimator is observed at much lower OPR values, and shows the merit of exploring appropriate threshold criteria.

4. Selection Criteria

Following the methodology developed for range unfolding Doppler-velocity and spectrum-width estimates from data containing multiple-trip echoes, a threshold based on the ratio of the EUT power to the sum of powers from other trips is used to determine the appropriate selection of the long- or short-PRT data. Several factors play into the selection of the thresholds, including the values of the Z_{DR}, ρ_{hv}, SNR, and σ_v estimates for both the EUT and overlaid echoes. The amount of bias and standard deviation degradation incurred in the case of overlaid echoes depends upon the relationship between the aforementioned meteorological variables.

The results presented in the previous section provide an impetus for three types of selection criteria. The first follows the "do no harm" mantra adhered to by algorithm developers, and determines the $\mathrm{T_{over}}$ value to be the OPR level at which none of the short-PRT estimate statistics are worse than those of the long-PRT estimates. Below the $\mathrm{T_{over}}$ threshold, the long-PRT estimates will be used, and thus no loss of quality would be incurred with respect to the current implementation. The $\mathrm{T_{over}}$ threshold requires that the criteria be met for the both the bias *and* standard deviation. Using this worst-case criterion, only short-PRT estimates with improved statistical performance are used, eliminating the possibility of unnecessary contamination and degradation of the meteorological data. This technique, however, also eliminates cases in which the overlaid statistics are better than the long-PRT data at lower OPR levels. It is apparent that the higher the $\mathrm{T_{over}}$ value, the less frequently the short-PRT estimates will be used.

A second possible selection rule relaxes the "do no harm" criterion slightly and allows the short-PRT estimate statistics to exceed those of the long-PRT estimates by 10 percent. This relaxation of the worst-case criterion allows for more instances of applicable cases for the use of the short PRT. While the 10-percent criterion allows the potential for a slight increase in bias and standard deviation, it also allows for a considerable increase in performance.

Both of the aforementioned selection rules require the use of a look up table which contains the $\mathrm{T_{over}}$ values for specific EUT parameters: SNR, Z_{DR}, σ_v, and ρ_{hv}. Such a table would be stored in memory and would only need to be generated once for each polarimetric variable (Z_{DR}, Φ_{DP}, ρ_{hv}). The performance of the techniques is limited by the fact that only information from the EUT is used. A third technique is an extension of the worst-case selection rule, and includes information about the overlaid echo as well. This would ensure that the best possible performance is achieved. A much larger look up table would be required to implement such a scheme, but the benefits could be substantial.

Figure 6 was generated to illustrate the implementation of the worst-case and 10% selection criteria. The shaded plots are the same percent improvement plots presented in Figure 4, but with vertical lines added to indicate the $\mathrm{T_{over}}$ values calculated using the worst-case (green) and 10% (red) selection criteria. It is apparent that the the 10% criteria would lower the $\mathrm{T_{over}}$ value, and in doing so would allow more range gates to use the short-PRT estimates. While a nominal degradation would occur in some cases, an overall improvement is observed (not shown).

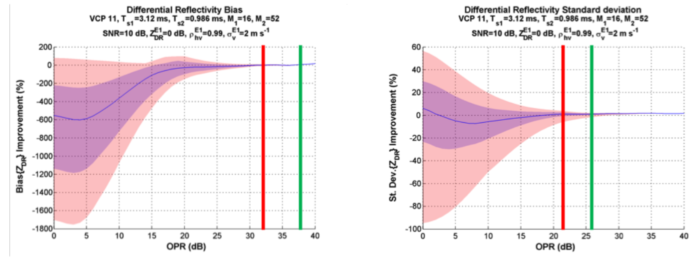

Figure 6: Illustration of the implementation of the worst-case and 10% selection criteria for VCP 11 Z_{DR} estimates. The shaded plots are the same as Figure 4, while the vertical green and red line represents the $\mathrm{T_{over}}$ value determined by the worst-case and 10% selection criteria, respectively. Note that the worst-case criteria has a considerably higher $\mathrm{T_{over}}$ value than the 10% criteria.

Table 1 and Table 2 indicate the $\mathrm{T_{over}}$ values determined by the worst-case and 10% criteria methods, along with the median improvement at that point for all overlaid-echo parameters.

As was noted earlier, the potential improvement and $\mathrm{T_{over}}$ value is dependent upon the EUT parameters. The $\mathrm{T_{over}}$ values presented in Table 1 are quite high, and do not impart a substantial improvement over the long-PRT estimates. However, the values in Table 2 represent a case in which the short-PRT estimates would be used for a wider range of OPR values, and the improvement is more substantial.

5. Conclusions

Over the course of this study, the use of polarimetric-variable estimates from both the surveillance and Doppler scans for the split cut portion of VCP 11 was explored. Extensive simulations were used to quantify the performance of the short-PRT estimates (with potential contamination from overlaid echoes) with respect to those from the long-PRT data. The performance was used in two selection rules designed to maximize the quality of the polarimetric-variable estimates. Further analysis is needed on real data to qualitatively confirm the improvement in performance, and to identify potential impacts on downstream processing schemes. Additional VCPs must be explored as well,

Table 2: SNR=10 dB, Z_{DR}=0 dB, σ_v=2 m s^{-1}, ρ_{hv}=0.99

	T_{over} **(Median Improvement (%)**				
	Bias{ Z_{DR}}	**St. Dev. { Z_{DR}}**	**St. Dev. { Φ_{DP}}**	**Bias{ ρ_{hv}}**	**St. Dev.{ ρ_{hv}}**
Worst Case	38 (7)	38 (1.5)	29 (1.5)	38 (11)	38 (2)
10%	32 (0)	32 (1.5)	20 (0.5)	38 (11)	38 (2)

Table 3: SNR=10 dB, Z_{DR}=3 dB, σ_v=6 m s^{-1}, ρ_{hv}=0.9

	T_{over} **(Median Improvement (%)**				
	Bias{ Z_{DR}}	**St. Dev. { Z_{DR}}**	**St. Dev. { Φ_{DP}}**	**Bias{ ρ_{hv}}**	**St. Dev.{ ρ_{hv}}**
Worst Case	19 (51)	19 (15)	12 (15)	28 (33.5)	28 (15.2)
10%	19 (51)	19 (15)	9 (16)	28 (33.5)	28 (15.2)

including those that make use of SZ2 coding. Extensions to more than two echoes can also be explored through the use of the simulator utilizing the techniques developed here.

Acknowledgments.

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