Theory and Concept of Operations for Multi-PRF Dealiasing Algorithm's VCP 112

W. David Zittel
ROC Applications Branch
March 19, 2019

1. Introduction

VCP 112 is a new volume coverage pattern that supports the Radar Operations Center's (ROC) effort to standardize volume coverage patterns (VCPs) used by field sites. VCP 112, like VCPs 12 and 212 has 14 defined elevation angles (0.5°, 0.9°, 1.3°, 1.8°, 2.4°, 3.1°, 4.0°, 5.1°, 6.4°, 8.0°, 10.0°, 12.5°, 15.6°, and 19.5°). Some sites are permitted an extra supplemental low elevation scan below 0.5° to improve coverage. VCP 112 replaces VCP 121 which was the last remaining VCP that used only 9 elevation angles (0.5°, 1.45°, 2.4°, 3.35°, 4.3°, 6.0°, 9.9°, 14.6°, and 19.5°). VCP 112, like its predecessor VCP 121, feeds data to the Multi-PRF (Pulse Repetition Frequency) Dealiasing Algorithm (MPDA) to dealias velocities and mitigate range folding (Conway et al., 1997).

1.2 Background – Evolution of MPDA and Its VCPs

The MPDA, with VCP 121, was first fielded in the spring of 2004 in Build 6. The MPDA mitigates range folding by combining Doppler data from up to three cuts at the same elevation angle, with each cut using a different PRF. Changing the PRF changes the unambiguous range and thus the areas that are shown as range folded. It further takes advantage of having up to three independent measurements of velocity for the same point in space. By adding multiples of the Nyquist velocity co-intervals, the MPDA computes alternative inbound/outbound velocity estimates for each independent value. A final, good velocity estimate is obtained where there is a clustering of similar velocities from the independent velocity estimates. If no good solution is found using three velocity estimates or if there are only 2 estimates available, the MPDA will try to find a reasonable solution using just velocity pairs not unlike a staggered PRT algorithm. Finally, if a solution cannot be found for velocity pairs or if there is only one velocity estimate available, the MPDA tries to adjust a velocity using Nyquist co-interval offsets to match nearby velocity estimates or a wind profile. By design in VCP 121, the MPDA specified three Doppler scans for elevation angles through 3.35° but only two scans at the 4.3° batch cut.

In the spring of 2008, VCP 121 was modified to specify that the first Doppler cut use the Sachidananda-Zrnic (SZ-2) phase coding technique (Zittel et al. 2008). The SZ-2 technique, first introduced in 2007, reduces range folding in split cuts (≤ 1.5° elevation) by extracting velocities from weak and strong trip echoes. A separate study by Crauder showed it was possible to obtain reasonable dealiasing results with just one SZ-2 scan and a companion contiguous Doppler scan (Crauder et al. 2008). The abstracts for these two papers are included as appendices to this document. At the time, the RDA would not support collecting two back-to-back SZ-2 scans. The rationale for using just two scans was to improve volume scan throughput time desired by field sites.

In the fall of 2017, with the intent to replace VCP 121 with another VCP that used common elevation angles, the option to use two back-to-back SZ-2 scans was explored and found to be feasible. The resulting VCP is VCP 112, which specifies pairs of SZ-2 scans with different PRFs at each split cut but uses the batch waveform between 1.8° elevation and 6.4° elevation. Above 6.4° elevation, as with other VCPs, the contiguous Doppler waveform is used. Table 1 provides a summary of the waveforms and PRFs used in VCP 112.

Table 1. PRF and waveforms used by elevation angle and RDA scan for the generic VCP 112. Note that sites with a supplemental low-level elevation below 0.5° elevation use the same PRFs as the 0.5° elevation angle. If SAILS is requested, the RPG will insert the sequence of scans for the lowest elevation angle at the midpoint of the volume scan, by time.

Elevation (deg)	Surveillance PRF	Doppler PRF	Waveform
0.5	1	-	SurveillanceSZ-2
0.5	-	8	Doppler SZ-2
0.5	-	4	Doppler SZ-2
0.9	1	-	Surveillance SZ-2
0.9	-	8	Doppler SZ-2
0.9	-	5	Doppler SZ-2
1.3	1	-	Surveillance SZ-2
1.3	-	8	Doppler SZ-2
1.3	-	6	Doppler SZ-2
1.8	3	2 through 8	Batch
2.4	4	2 through 8	Batch
3.1	5	2 through 8	Batch
4.0	6	2 through 8	Batch
5.1	6	2 through 8	Batch
6.4	6	2 through 8	Batch
8.0	-	6	Contiguous Doppler
10.0	-	7	Contiguous Doppler
12.5	-	8	Contiguous Doppler
15.6	-	8	Contiguous Doppler
19.5	-	8	Contiguous Doppler

1.3 PRF Selection

The elevation angles 0.5°, 0.9°, and 1.3°, for which the MPDA dealiasing algorithm is used, have predefined PRFs pairings that cannot be changed. The 0.5° elevation uses PRFs 8 and 4, the 0.9° elevation uses PRFs 8 and 5, and the 1.3° elevation uses PRFs 8 and 6. For batch elevation angles, PRFs 2 through 8 may be selected manually or by allowing an automated technique to make the selection. For higher elevation angles that use the Contiguous Doppler waveform, the PRFs cannot be changed.

Choosing the optimal pair of PRFs for the split cuts for VCP 112 requires pairing PRFs such that the range to the end of first trip for the lower PRF extends beyond the region with range folding at the start of second trip for the higher PRF. Also, to a lesser degree the same logic applies to third trip. Table 2 provides lists the PRF numbers and associated values for the first trip unambiguous range and the Nyquist velocity associated with the PRF. The choice of pairings was determined by examining the continuity of coverage for several data cases collected during the fall of 2017. Figure 1 is an example from October 7, 2017 at 0.5° elevation that shows how the coverage of PRF 4 (green line) nicely fills in the range-folded regions of PRF8 (red line) and vice versa. The blue line shows the coverage from VCP 112.

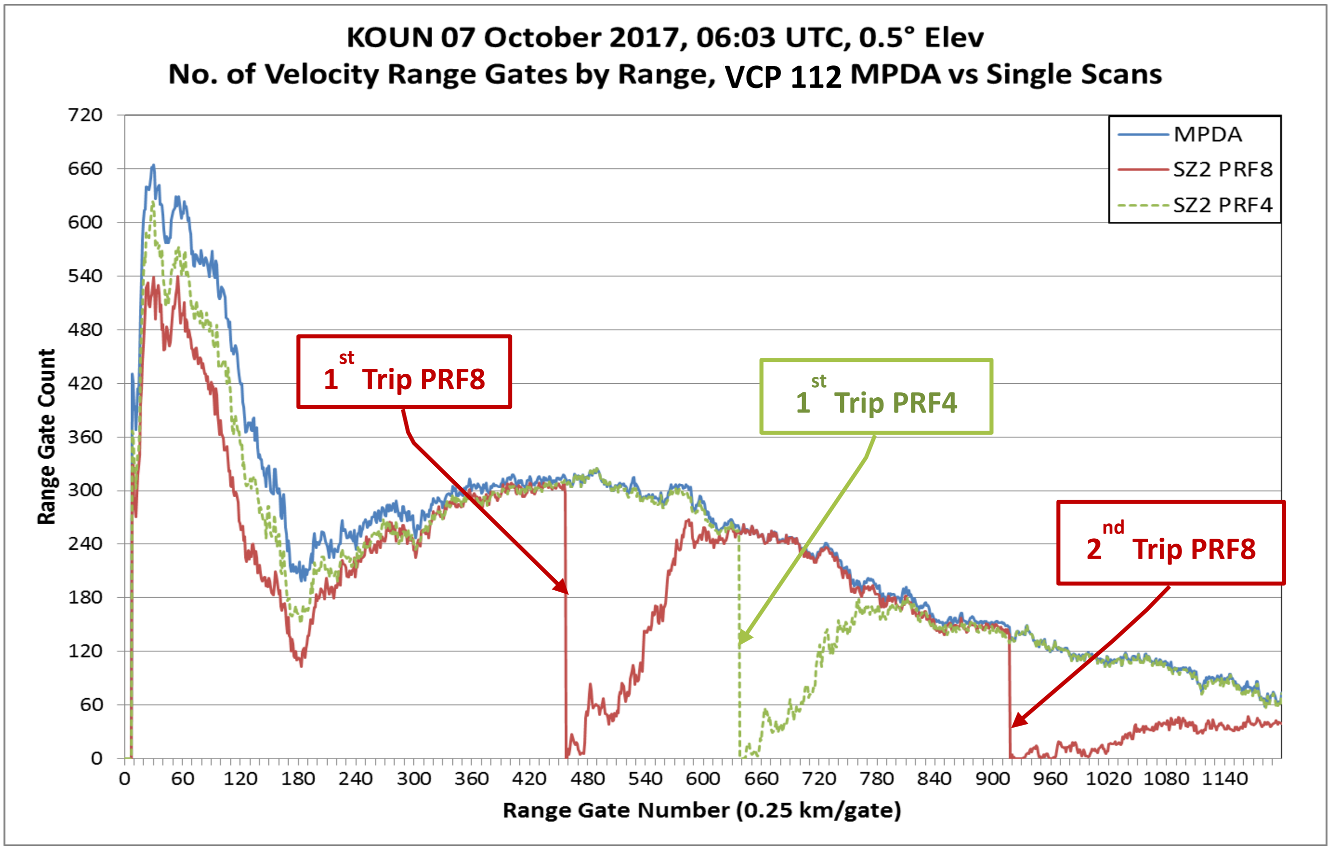

Figure 1. This figure shows the number of sample volume bins with good velocity data in concentric rings as a function of range by range bin number. There are 720 bins maximum possible for any given range. 1200 is equivalent to 300 km, the maximum range of coverage. Bins that have no data or are range folded are not tallied.

1.4 Use of Current Wind Profile Data

VCP 112 relies on the Current Wind Profile data to help dealias data at far ranges, especially beyond 230 km. At this range, often the only velocity data available are the weak trip velocity from the lower of the two paired PRFs. The Current Wind Profile data are refreshed hourly from model wind data and updated each volume scan by the Enhanced Velocity Wind Profile. It is possible that isolated patches of velocity that do not align with the free atmosphere (geostrophic) wind could be dealiased incorrectly. An example might be from a hurricane eye just entering the range of coverage.

Table 2. Unambiguous range and corresponding Nyquist velocities for separate surveillance and Doppler PRF tables introduced in Build 18. See Table 1 for the PRFs used by VCP 112. Shaded boxes in this table are not used by VCP 112 at any elevation angle.

Surveillance PRF	1	2	3	4	5	6	7	8
R_{max} (km)	466.00	429.00	386.00	336.00	293.00	249.00	209.00	174.00
V_{Nyq} (m s^{-1})	8.05	8.74	9.72	11.16	12.80	15.06	17.94	21.55
Doppler PRF	1	2	3	4	5	6	7	8
R_{max} (km)	336.00	187.00	175.00	162.00	148.00	137.00	127.00	117.00
V_{Nyq} (m s^{-1})	11.16	20.05	21.43	23.15	25.34	27.37	29.53	32.05

1.5 AVSET, SAILS, and MRLE

VCP 112, like other precipitation mode VCPs, allows AVSET to terminate a volume scan as low as 6.4° if no echo is present aloft. It also allows SAILS to collect one extra elevation sequence at the lowest specified elevation angle midway through the volume scan. If a full volume scan through 19.5° is being run, the extra SAILS will fall between the 1.8° and 2.4° elevation cuts. If AVSET truncates the volume scan at 6.4°, SAILS will occur after the1.3° elevation cut. Use of MRLE currently is not allowed in VCP 112 as this would unacceptably lengthen the volume scan time.

1.6 Retention of Range-folded Data

VCP 112 checks for range-folded bins at the same point in space for both Doppler scans. If so, the corresponding bin in the output velocity field is shown as range folded. Otherwise, the output velocity field will have either a valid velocity or no velocity. This is different from VCP 121 which, for split cuts, put all range folded velocity bins from the first Doppler cut into the output velocity field unless they could be replaced with a velocity estimate from the other two Doppler cuts. Range-folded retention logic for VCP 112, though, is the same as used for VCP 121 at elevation 4.3° which also used only two Doppler scans.

2. Operational Considerations

2.1 When to Use VCP 112

VCP 112 should be considered for use in large-scale systems or in convective squall lines not easily covered by an existing single PRF Doppler scan VCP. In such instances, use of a single PRF may obscure important data due to range folding. Moreover, the constantly changing range at which range folding occurs due to changing PRFs can be annoying. By combining velocity data from scans using different PRFs it is possible to eliminate most range folding at the start of the second trip for each PRF and the start of third trip for the higher PRF 8. This feature of the MPDA provides better continuity in velocity images from one volume scan to the next. While the PRF diversity that is now available in other VCPs helps minimize range folding, especially with the lower PRFs 2 and 3, the lower Nyquist velocity associated with these PRFs may introduce velocity dealiasing errors in the two-dimensional velocity dealiasing algorithm.

2.2 Examples

2.2.1 Severe Storm Case

The four-panel graphic (Figures 2a-d) below is from data collected on the ROC's testbed WSR-88D (KCRI) on May 3, 2018 at 02:18 UTC at 0.5° elevation. Figure 2a shows the reflectivity which consists of a broken line of strong to severe storms. The velocity data for each PRF scan can be obtained by temporarily disabling the MPDA during offline testing. The resulting velocity fields, dealiased by the 2DVDA, are shown for PRFs 8 and 5 in panels b and c, respectively. Panel d shows the results obtained from the MPDA. Note the strong outflow east of the radar apparent in all three velocity images. The pronounced bands of range folded data in panels b and c are not present in panel d obtained by the MPDA.

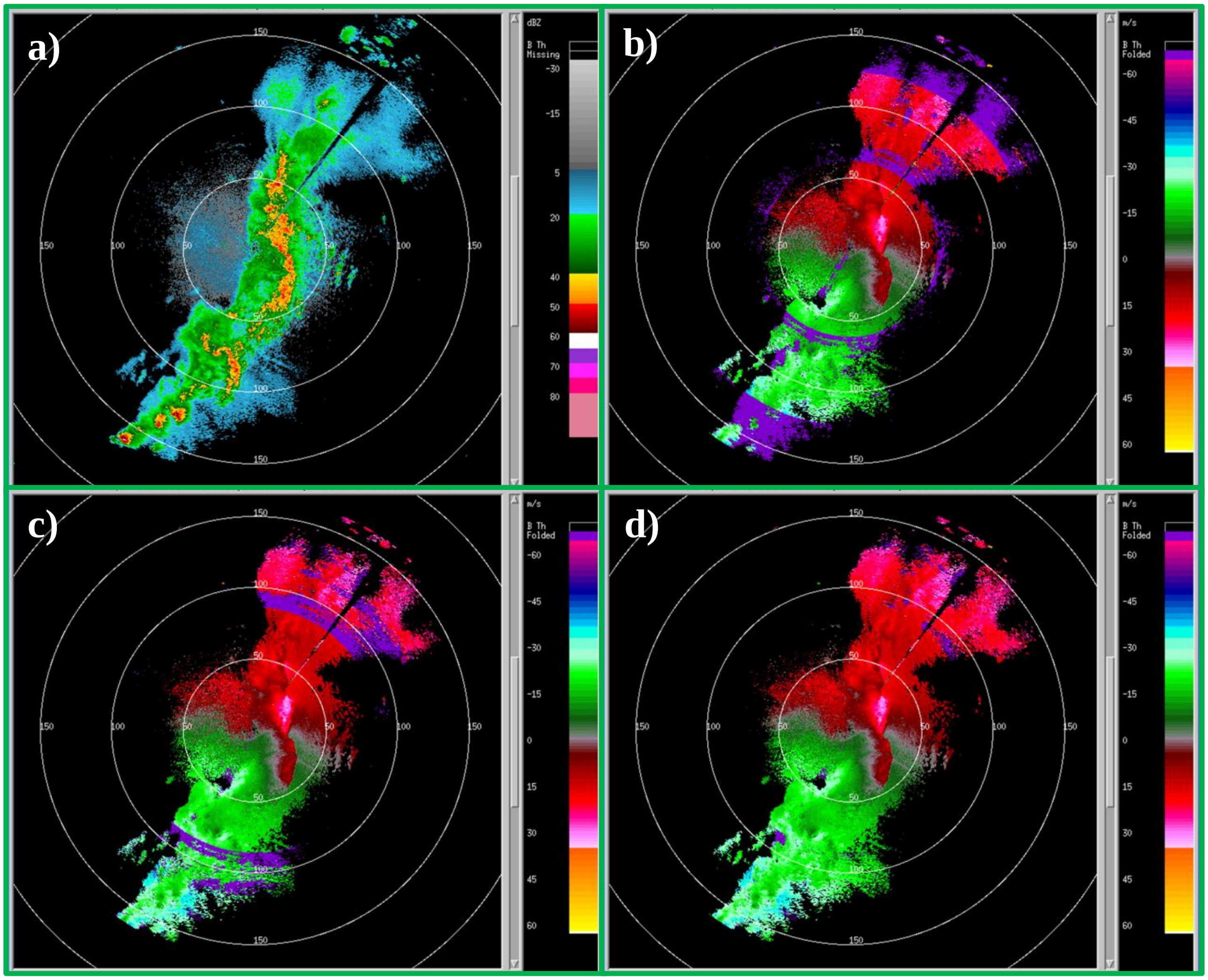

Figure 2. Reflectivity (panel a) and dealiased velocity fields for PRF8 (panel b), PRF6 (panel c), and the MPDA (panel d) for KCRI on 3 May 2018 at 02:28 UTC. Note the lack of a pronounced ring of range-folded data for the MPDA in panel d. Elevation is at 0.5°. Range rings are every 50 km.

The four-panel graphic (Figures 3a-d) below shows reflectivity and velocity data collected on the KOUN testbed WSR-88D radar collected on October 22, 2017 at 04:20Z at 0.9° elevation. Figure 3a shows the reflectivity for a squall line east of the radar and moving away. Behind the squall line is an extensive rain shield. Note the extensive region of range folded velocity data in Figure 3b with the PRF8 velocity scan. Figure 3c has one band of range folding and some data sparse areas in 2nd trip echo. Both figures 3b and 3c were dealiased using the 2DVDA. Figure 3d, showing the dealiased results using the MPDA, removes nearly all the range folded data.

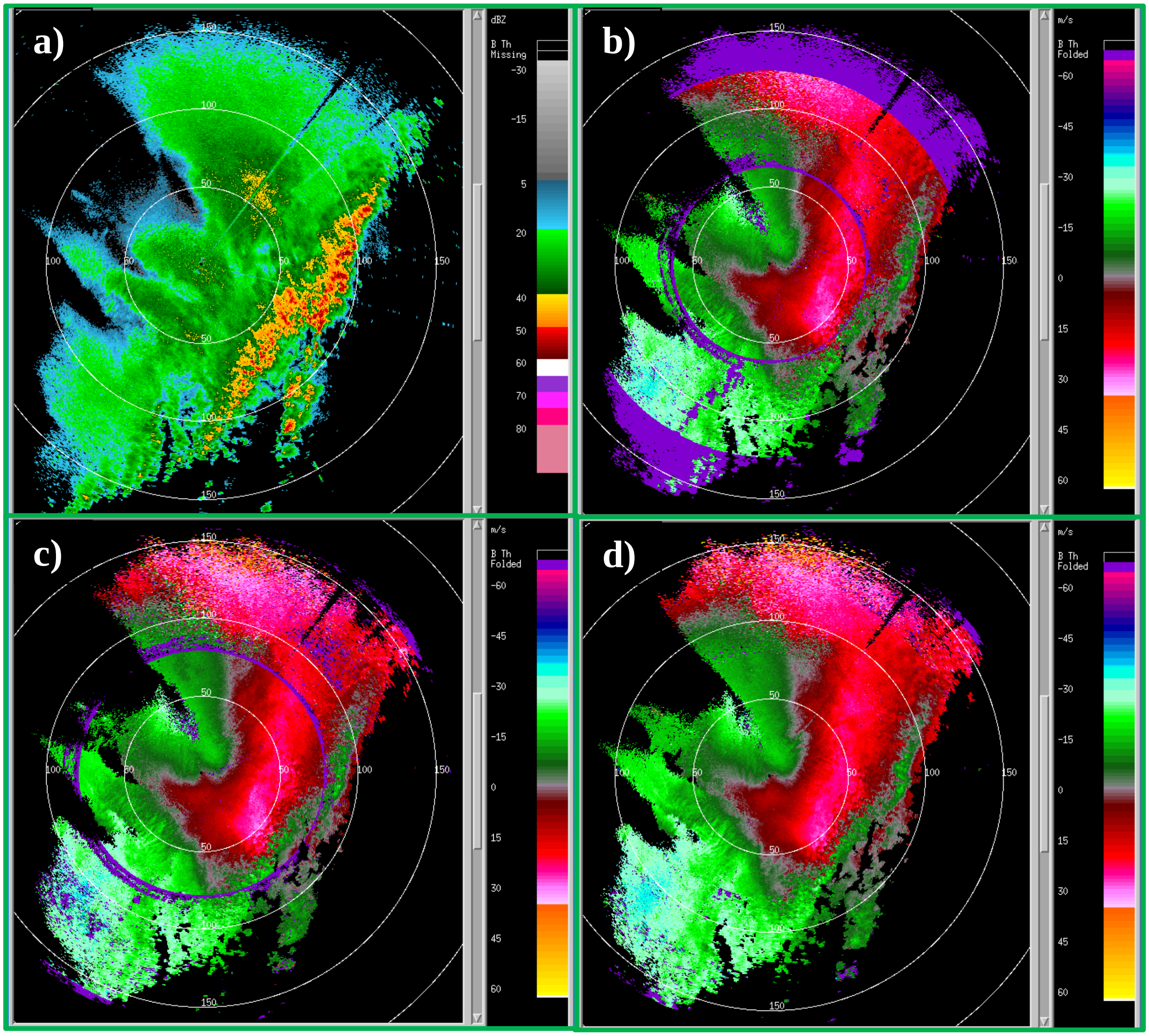

Figure 3 Reflectivity (panel a) and dealiased velocity fields for PRF8 (panel b, PRF5 (panel c) and the MPDA (panel d) for KOUN on October 22, 2017 at 04:20 UTC at 0.9° elevation. Note the lack of range-folded data beyond 230 km for the MPDA in panel d. Range rings are every 50 km.

2.2.3 Strong Wind Shear

On April 7, 2018 a band of light showers moved across central Oklahoma. This case is notable for the sudden change in wind direction between 6 and 7 kft above MSL from north-northeasterly flow to westerly flow. Figure 4a shows the reflectivity, Figures 4b and 4c show the 2DVDA dealiased velocity data for PRFs 8 and 4, respectively, and Figure 4d shows the MPDA dealiased velocity data. Of note is the sudden change in the radial velocity data from outbound west of the radar (shown as red) to fairly strongly inbound shown in green. There is good agreement between the 2DVDA dealiased fields and the MPDA while minimizing range folded regions. Figure 5 shows the VAD Wind Profile product encompassing the time in question. The transition zone is clearly shown and is stable over time. Soundings from OUN at 00 and 12 UTC (not shown) confirm the VWP product analyses.

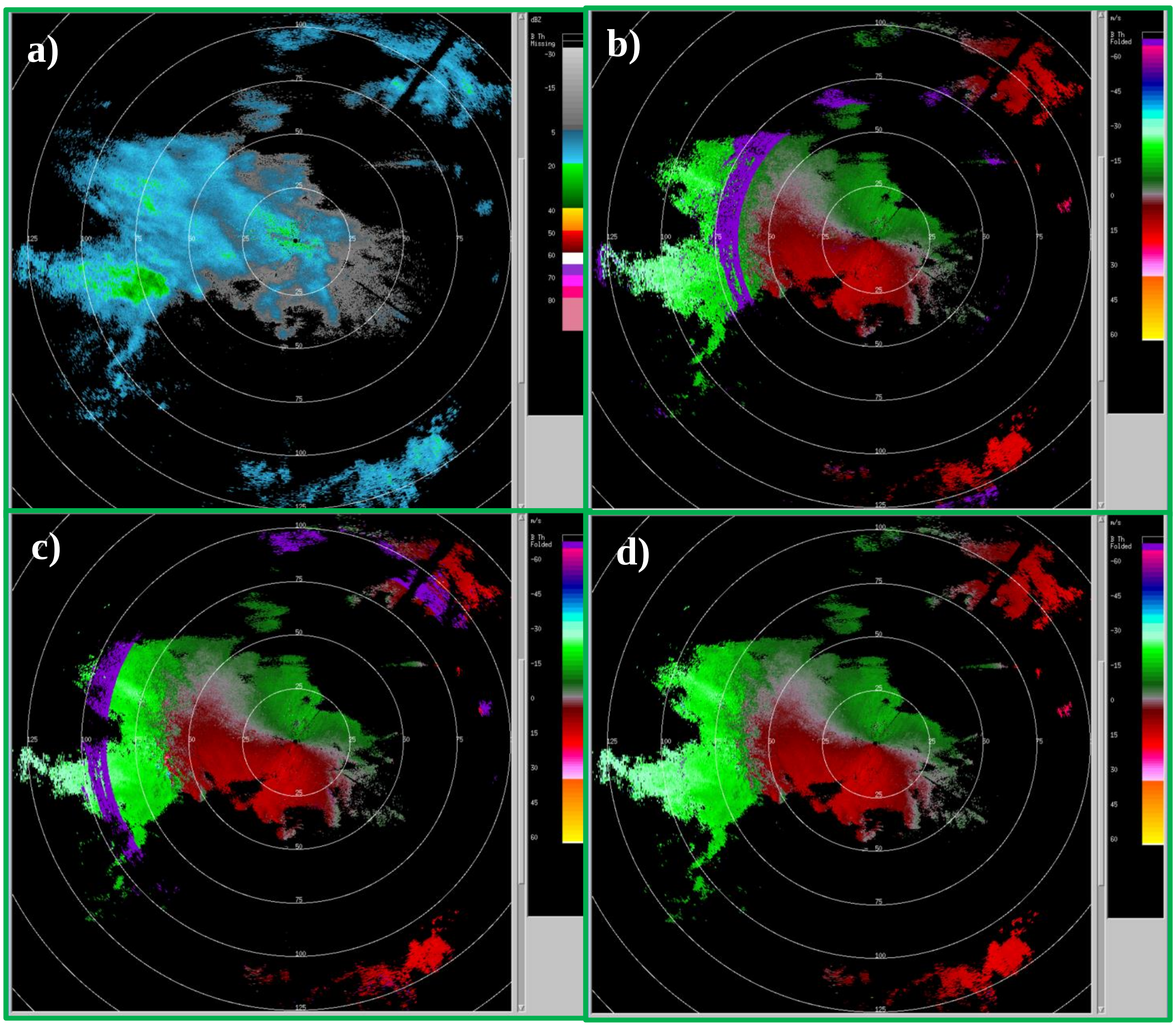

Figure 4. Dealiasing results from KCRI on 07 April 2018 at 09:26 UTC at 0.5° elevation. Reflectivity is shown in panel a, PRF8 dealiased velocity is shown in panel b, PRF4 dealiased velocity is shown in panel c, and the results from the MPDA are shown in panel d.

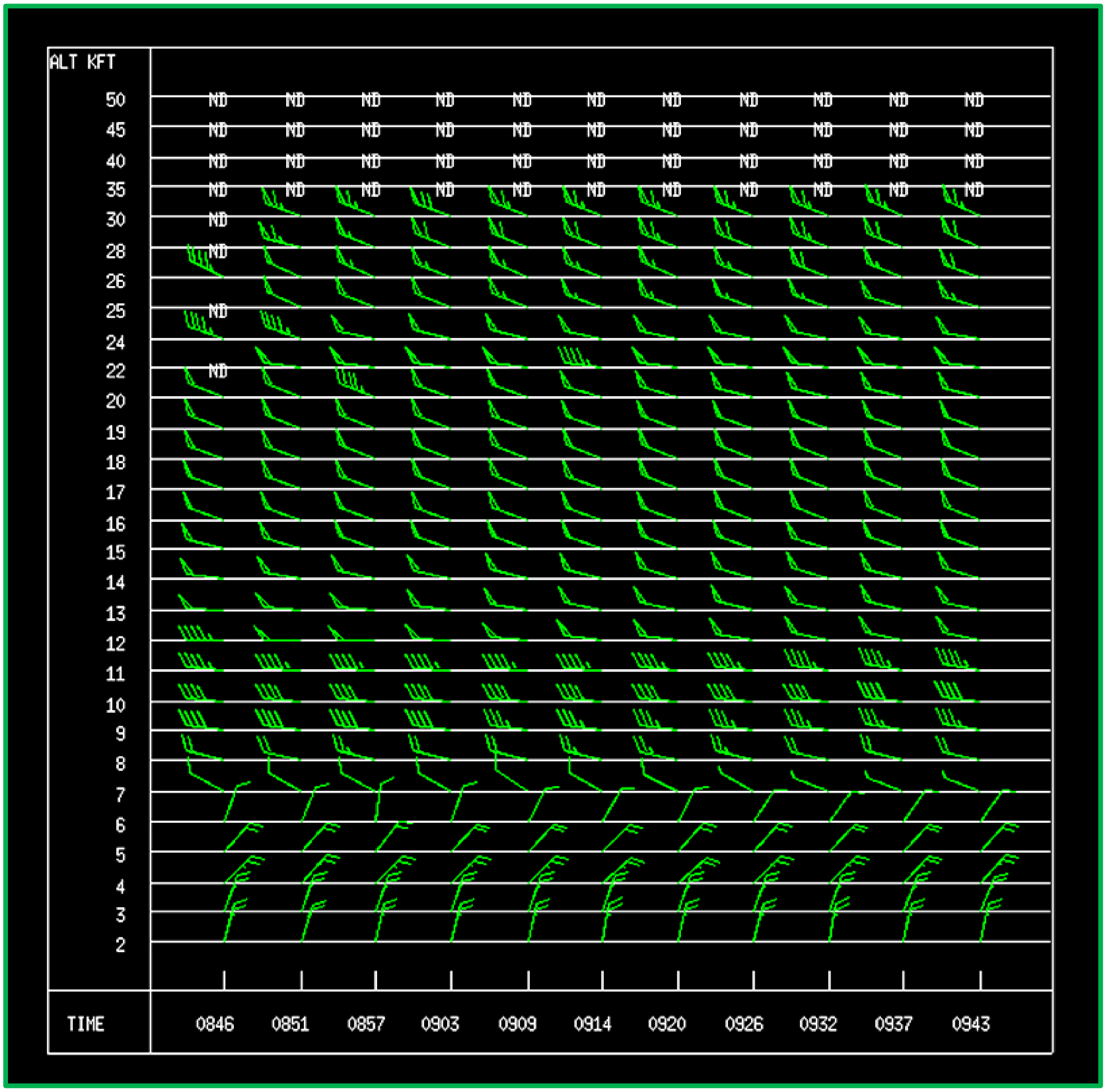

Figure 5. VAD Wind Profile product from the KOUN radar for April 7,2019 from 08:46 to 09:43 UTC. Clearly seen is the change from north-northeasterly winds from the surface through 6 to 7 kft above MSL where the wind changes to a strong westerly direction.

3. VCP 112 Volume Scan Update Rate

The volume scan update rate for VCP 112 can vary from as short as about four and a half minutes to seven and a half minutes depending on other features that are enabled. The shortest time is provided when AVSET (Automated Volume Scan Early Termination) is enabled and terminates at 6.4°. A full volume of VCP 112 completes in about five and a third minutes. If SAILS (Supplemental Adaptive Intra-Volume Low-Level Scan) is enabled, the full volume scan throughput time increases to about six and a third minutes. Finally, if a site has a supplemental low-elevation scan enabled, the throughput time.for VCP 112 increases by a minute. The times shown in Table 3 do not reflect the retrace time from highest elevation down to a low scan which typically is 2.5 to 3 seconds. The time to move from a lower elevation angle to a higher elevation angle is approximately half a second. And the time to change PRFs and rotation rates at the same elevation angle is about one-tenth of second (Olen Boydsten, personal communication). The cumulative transition times for the 20-RDA scan sequence in Table 3 is ~10 sec resulting in a 05:32 update rate.

Table 3. Volume scan update rates for VCP 112 for combinations of AVSET, SAILS, and supplemental low elevation scans. See text for estimated time to transition between scans.

# RDA Scans	# RPG Scans	AVSET	SAILS	Supplemental Low Elev	Time (sec)	Time (mm:ss)
15	9	6.4°	Off	No	272	04:32
20	14	Off	Off	No	322	05:22
23	15	Off	On	No	385	06:23
26	16	Off	On	Yes	447	07:27

4. Changes to Adaptable Parameters

With the fielding of VCP 112 two adaptable parameters for the MPDA are no longer needed. They are: Threshold (Fix Trip Minimum Bin) and Threshold (Fix Trip Maximum Value). (Figure 6 shows the adaptable parameters as they appeared in RPG builds prior to Build 19.) Historically, because of signal processing errors at or near the end of the unambiguous range trips, velocity data were prone to bad values. To eliminate erroneous solutions, the MPDA removed narrow concentric bands of velocity data in each velocity scan prior to finding a solution by combining the velocities. Velocity images for the MPDA would occasionally have missing values at or near the end of the 2nd trip echo. With the change to two scans of SZ-2 Doppler data for the MPDA and improvements in signal processing for the SZ-2 mode, the likelihood of bad estimates is greatly reduced and the two Threshold values have been set to zero (0). This eliminates the need to adjust these values and eliminates bands of missing data. See Figure 7 for a graphical image of the adaptable parameter screen for the MPDA for Build 19.

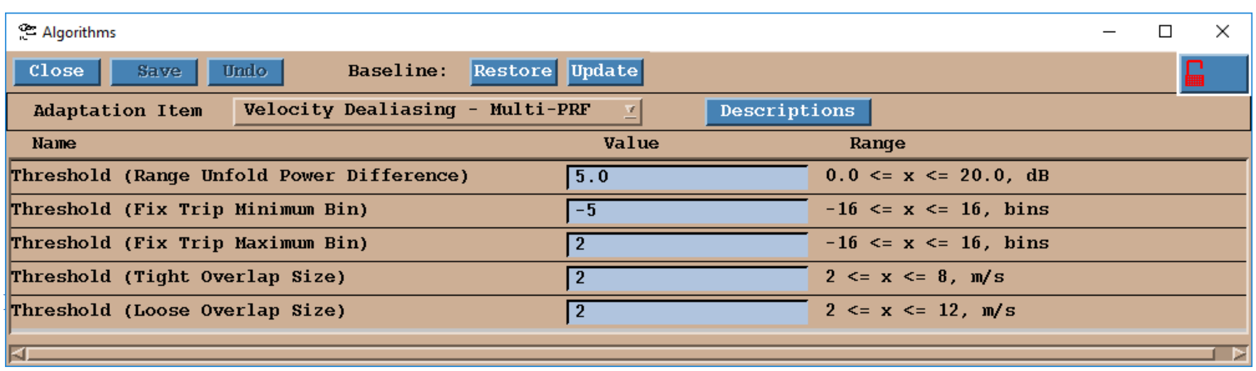

Figure 6. Graphical interface screen for MPDA adaptable parameters for RPG software builds prior to Build 19.

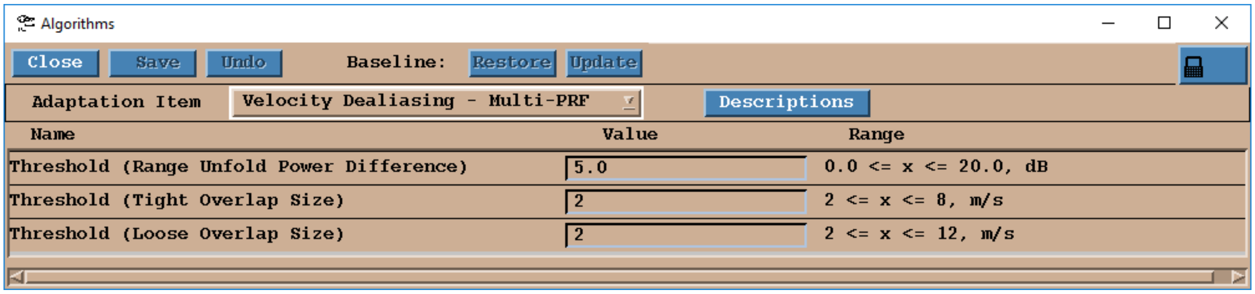

Figure 7. Graphical interface for the MPDA adaptable parameters for the RPG Build 19 software. The adaptable parameters Threshold (Fix Trip Minimum Bin) and Threshold (Fix Trip Maximum Bin) are no longer editable.

5. Spectrum Width Estimates

The MPDA stores both velocity and spectrum width estimates from each of the Doppler scans. After choosing a velocity from one of the two Doppler scans for the output velocity field, the MPDA selects the corresponding spectrum width value from the same Doppler scan for the output for the spectrum width field. From the "Concept of Operations For the SZ-2 Range-folding Mitigation Technique" document, the variance of the spectrum width estimates from weak trip echo is unacceptably high. Instead SZ-2 computes the spectrum width from the surveillance scan. Because of the low PRF used for the surveillance scan (the Nyquist velocity is about 11 m s-1 or 22 kt), the effective maximum meaningful value for the spectrum width is about 6 m/s in weak trip echoes. By design, if the computed spectrum width in weak trip exceeds 6 m s^{-1} (12 kt) for a particular bin, the bin is indicated as range folded. Consequently, there may be slightly more bins indicated as range folded for spectrum width data than for velocity data. (Adapted from *Concept of Operations for the Enhanced VCP 121 To Mitigate Range Aliasing*.)

6. Backwards Compatibility

To enhance the performance of VCP 112 using only 2 Doppler scans at the same elevation required small changes to internal scaling parameters and changes to the calling sequence of functions within the MPDA. Within the MPDA a check is made to determine which version of the RPG software is being run. If the version is prior to Build 19, the original settings of the MPDA are run assuming data is from VCP 121. Otherwise, the updated version is run to support VCP 112.

BIBLIOGRAPHY

Conway, J.W. K.D. Hondl, and M.D. Eilts, 1997: Minimizing the Doppler Dilemma using a unique redundant scanning strategy and multiple pulse repetition frequency dealiasing algorithm. *Preprints: 28th Conf.on Radar Meteor*, Austin, TX, AMS, 315-316.

Crauder, D.C. and W.D. Zittel, 2008: Evaluation of a faster scanning strategy for the WSR-88D combined range aliasing mitigation techniques. In *24th Conf. on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*, New Orleans, 21-25 January (2008).

Zittel, W. David, D. S. Saxion, R. D. Rhoton, and D. C. Crauder, 2008: Combined WSR-88D technique to reduce range aliasing using phase coding and multiple Doppler scans. In *24th Conf. on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*, , New Orleans, 21-25 January (2008).

Zittel, W.D., and T. Wiegman, 2005: VCP 121 and the multi-PRF dealiasing algorithm. *NEXRAD Now*, **14**, 9-15.

Zittel, W. David: "Concept of Operations for the Enhanced VCP 121 to Mitigate Range Aliasing" (Radar Operations Center, 2008); available online from Warning Decision Training Division.

Zittel, W. David: "Concept of Operations for the SZ-2 Range-folding Mitigation Technique" (Radar Operations Center, 2007); available online from Warning Decision Training Division.

Appendix 1. Abstract of paper presented at the 24th IIPS conference by Zittel et al., 2008.

In the spring of 2008 the Radar Operations Center (ROC) plans to upgrade an operational WSR-88D volume coverage pattern (VCP 121). The upgrade reduces range aliasing by combining the Sachidananda-Zrnic phase coding algorithm (designated SZ-2) with a multi-scan algorithm called the Multiple Pulse Repetition Frequency (PRF) Dealiasing Algorithm (MPDA). The MPDA, fielded in 2004, combines velocity data from up to three sweeps at the same elevation angle but with different PRFs. Velocity data that is aliased using one PRF may not be range aliased using another PRF. The SZ-2 algorithm separates weak trip echo from strong trip echo by encoding successive pulses through a defined sequence of phase shifts to reduce range aliasing. The MPDA frequently leaves range aliased data beyond 175 km. The SZ-2 algorithm performs well at long range but has residual range aliased data at the start of its second trip echo. Thus, when combined, the two techniques complement each other.

Four data cases with widespread precipitation were collected on the ROC's test bed WSR-88D during the fall and winter of 2006. Analysis of the data indicates velocity recovery of 98 percent (by area) out to a range of 230 km is possible by combining the techniques. Use of SZ-2 by itself provides velocity recovery of nearly 92 percent of the data field. Use of the MPDA alone recovers 65 to 70 percent. A field test is being conducted during the latter half of calendar year 2007 at eight field sites to validate the performance under meteorologically and geographically diverse conditions.

Appendix 2. Abstract of paper presented at the 24th IIPS conference by D. Crauder and W.D. Zittel, 2008.

In a recent survey of WSR-88D sites, operational staff indicated a desire for faster volume coverage patterns (VCPs) that also mitigate range aliasing. In 2004, the Radar Operations Center (ROC) fielded a new technique called the Multiple Pulse Repetition Frequency (PRF) Dealiasing Algorithm (MPDA) that combines three sequential Doppler scans with PRFs of about 1300, 1100, and 850 Hz, respectively, to mitigate range aliasing. Another technique to mitigate range aliasing, the Sachidananda-Zrnic phase coding algorithm (SZ-2), is being fielded in the summer of 2007. SZ-2 uses advanced signal processing to separate strong trip from weak trip signal. The two algorithms, when combined, recover an average of 98 percent of velocity area data out to 230 km. One major drawback with the combined technique is that a volume scan takes about five minutes and forty-five seconds to complete.

The ROC has investigated using two instead of three Doppler scans at each of the two lowest elevation angles. This is possible because the SZ-2 algorithm provides the bulk of the velocity recovery. Using two scans reduces the volume scan time about thirty seconds. Five data cases collected from the ROC's test bed WSR-88D were analyzed. Four cases with widespread precipitation were collected during the fall and winter 2006. The fifth case, a mesoscale convective system (MCS), was collected in June 2007. Using two instead of three Doppler scans yields an average velocity area recovery of 96.87 percent for the four widespread precipitation cases and 96.65 percent for the MCS case. Velocity dealiasing errors were also scored. Starting with a score of 100, points were deducted for different sized errors in the velocity field. For the widespread precipitation cases, using two instead of three Doppler scans decreased the number of errors slightly (0.045 percent decrease in errors); for the MCS there was a 1.70 percent increase in errors. These initial results support operationally fielding the combined algorithms with the middle (1100 Hz PRF) scan removed thus helping to meet the needs of radar sites.