7C.7 COMPARISON OF A 2-D VELOCITY DEALIASING ALGORITHM TO THE LEGACY WSR-88D VELOCITY DEALIASING ALGORITHM DURING HURRICANE IRENE

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1. INTRODUCTION

In the fall of 2012 the Radar Operations Center (ROC) plans to start fielding a two-dimensional velocity dealiasing algorithm (2DVDA) to replace the legacy Velocity Dealiasing Algorithm (VDA) as the primary velocity dealiasing tool for the Weather Surveillance Radar-1988 Doppler (WSR-88D). The 2DVDA, more robust than the current VDA, has been tested under a wide variety of weather situations and in all cases reduces the severity and frequency of dealiasing errors over the legacy VDA. One type of weather event for which improvement is especially pronounced is hurricanes. The purpose of this paper is to report on the performance of the new 2DVDA on Hurricane Irene from several WSR-88Ds as it traveled up the eastern U.S. seaboard.

2. BACKGROUND

Currently, the WSR-88D has available two velocity dealiasing schemes, the VDA and the Multiple Pulse Repetition Frequency (PRF) Dealiasing Algorithm (MPDA). The VDA remains virtually unchanged since the deployment of the legacy WSR-88Ds. It primarily uses radial continuity, an average of nearby velocity neighbors, or an Environmental Wind Table (EWT) to help resolve winds exceeding the maximum unambiguous velocity or Nyquist Velocity, V_N (Eilts and Smith, 1990). V_N ranges between 21 and 35 m s^{-1} for the WSR-88D's precipitation Volume Coverage Patterns (VCPs): VCPs 11, 12, 21, 211, 212, and 221 and the clear air VCP 32. The long-pulse clear air VCP 31 has a much smaller V_N of only about 11.5 m s^{-1}. While generally reliable, the VDA can fail: 1) under strong shear conditions; 2) in velocity data with moving clutter such as vehicles or wind turbines; 3) in areas with weak echoes; 4) when the V_N is much lower than the prevailing winds; or 5) where the values in the EWT are not representative of the local storm winds. The MPDA, fielded in 2004 as VCP 121, takes multiple scans of velocity data at the same elevation using up to three different PRFs (Zittel and Wiegman 2005). It can dealias velocity with a high degree of reliability where there is more than one velocity estimate available and, because range folding occurs at different ranges for the PRFs, it can mostly be eliminated out to 230 km especially with the addition of phase coding (Zittel et al. 2008). However, the utility of the MPDA in VCP 121 is limited during rapidly changing weather events because the additional scans required increases the volume scan time to nearly 6 minutes. VCP 121's utility is further diminished because it has only nine unique elevation angles with which to interrogate storm structure.

3. 2DVDA OVERVIEW

The 2DVDA, originally developed in the Research Applications Program at the National Center for Atmospheric Research by Jing and Wiener (1993), attempts to dealias connected two-dimensional regions within an elevation scan by minimizing all detected velocity discontinuities. It calculates the difference between a gate and the neighboring gates, puts paired gates into a smoothness function, and applies a least squares method to find suitable velocity values which minimize the smoothness function. To realize the full potential of the two-dimensional approach, the 2DVDA must be applied to a full elevation scan. This is done in two steps. In the first step the full field is used to generate an environmental wind table. In order to conserve computer CPU and memory resources, the 2DVDA may sub-sample complex, large fields. This is done by gridding a velocity field azimuthally and radially and computing a median velocity value for the center of each grid. The second step partitions the elevation scan, and the 2DVDA then dealiases smaller features such as mesocyclones and tornado vortex signatures. Finally, the internally generated environmental wind table is used to place small isolated regions in the correct Nyquist co-interval, $\pm 2kV_N$ where k is an integer.

A newer version of the basic 2DVDA, developed by ROC personnel and described by Witt et al. (2009, hereafter WBJ09) applies a weighting factor to the velocity differences. The

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closer the difference is to 0 or $2V_N$, the greater the weight that is given to the velocity difference. As the velocity difference approaches V_N, the weight goes to 0. Use of the weighting factor reduces or eliminates the contribution of noisy or unreliable data to the optimization setting. A suggestion mentioned by WBJ09 to improve the dealiasing further was to remove velocity data that is associated with high spectrum width before applying the 2DVDA. In the version of the 2DVDA being fielded for the WSR-88Ds, spectrum width data are used to weight the corresponding velocity differences. Differences associated with high spectrum width receive a smaller weighting during the global optimization of the algorithm. The spectrum width and velocity difference weights are multiplied together to produce a final weight. Another enhancement is to treat as separate regions two areas connected by a narrow bridge of noisy velocity data. Finally, the fielded version of the 2DVDA temporarily removes velocity data considered to be contaminated by side lobes. These velocities typically are near zero. The velocity data are restored after the rest of the field has been dealiased by comparing them to nearby data already dealiased and adjusting them by $\pm 2kV_N$.

The 2DVDA is not expected to cause any perceptible delay in product availability. The 2DVDA can be used with all VCPs except VCP 121 which uses the MPDA. For all other VCPs except VCP 31, a site may choose to use different Doppler PRFs for different azimuthally-defined sectors within an elevation cut to reduce range folding in that sector. When "sectorized" PRFs are used, the 2DVDA cannot be used. Instead, the RPG automatically reverts to the legacy VDA. Once a site switches back to using the same PRF for a scan, the 2DVDA will again be invoked. A site will have the option of reverting to the legacy VDA and disabling the 2DVDA.

4. METHODOLOGY

Unlike previous studies by WBJ09 and Langlieb and Tribout (2010, hereafter LT10) that compared the goodness of the 2DVDA to the VDA by examining velocity products in great detail and tabulating defects or errors in velocity dealiasing we displayed a full-range image of each velocity product and simply tabulated whether or not velocity dealiasing errors were observed. Like LT10 we characterized the size of the errors as small (~1 to 100 km^2), medium (~100 to 10,000 km^2), or large (>10,000 km^2). Because it is rare that any velocity field is completely free of errors due to ground clutter, moving targets, blockage, interference, noise in second trip, etc., we did not tabulate very small, random errors deemed not operationally significant. Like WBJ09 we included in our analysis super resolution (SR) velocity products (½ deg resolution in azimuth) for elevation angles at or below 1.5 deg elevation and 1 deg resolution products from all elevations.

Velocity products were generated in real time from live Level 2 data feeds using multiple pairs of non-operational Radar Product Generator (RPG) platforms in the ROC Applications Branch. One of each RPG pair used the legacy VDA while the second RPG used the 2DVDA. Files containing the products were saved for review afterwards. Data from the following WSR-88Ds were included in the evaluation: KAMX (Miami, FL), KMLB (Melbourne, FL), KCLX (Charleston, SC), KLTX (Wilmington, NC), KMHX (Morehead City, NC), KAKQ (Wakefield, VA), KLWX (Sterling, VA), and KOKX (Upton, NY). Figure 1 shows, geographically, the radars included in the evaluation and the number of volumes of data for each radar. For KLWX and KLTX, data gaps in time were filled in by retrieving Level 2 Archive data from the National Climatic Data Center and replaying the data.

Sites most often used VCP 12 or 212 (1471 volumes) while VCPs 21 or 221 were used less frequently (219 volumes). Results were tabulated by radar and by elevation angle. The specific elevation angles (cuts) for the VCPs and their pairing are shown in Table 1. In this table the elevation angles have been grouped by scan (waveform) type: split cuts, batch cuts, and contiguous Doppler (CD) cuts. In split cuts, a surveillance scan with a low PRF is followed by a scan with a high PRF scan to obtain Doppler data. Batch cuts alternate pulses at a low PRF with pulses at a high PRF on a radial-by-radial basis. For both the split cuts and the batch cuts, the low-PRF reflectivity data are used to range unfold the Doppler data. Contiguous Doppler cuts use only a high PRF to obtain both reflectivity and Doppler data because range folding is not an issue.

The number of products evaluated for each elevation angle (or paired elevation angles) is simply the total number of volume scans. For instance, at 0.5 deg elevation a total of 1690 SR velocity products were evaluated while at 0.9 deg elevation only 1471 SR products were evaluated. The total number of products evaluated for each algorithm was 9702, 9702, and 8012 for split, batch, and CD cuts, respectively. Note, split cuts include both ½ deg and 1 deg resolution products.

5. RESULTS FOR HURRICANE IRENE

For all sites and all elevations the 2DVDA consistently had fewer errors than did the legacy VDA. Table 2 shows the frequency of errors for all sites by elevation for the SR products in split cuts. The total number of SR errors for the legacy VDA is 581 while the 2DVDA had only 41 which is more than an order of magnitude smaller. The average error rate (100 x total error count/(total number of products)) is 11.98% for the legacy VDA and 0.85% for the 2DVDA.

Table 3 shows the split cut dealiasing results for the 1 deg resolution velocity products. The error rates between the ½ deg and 1 deg resolution products are roughly comparable. The legacy VDA frequency of dealiasing errors is slightly lower for the 1 deg vs. the ½ deg resolution products (542 vs. 581). There is ~50% increase in dealiasing errors for the 2DVDA for the 1 deg resolution products over the ½ deg resolution products (62 vs. 41). Still, the 2DVDA average error rate of 1.28% is almost an order of magnitude smaller than the legacy VDA's average error rate of 11.17%.

Table 4 shows the number of errors for the batch and contiguous Doppler cuts. For the batch cuts the dealiasing errors are mostly confined to the lowest two elevation angles at 1.8 and 2.4 deg for either dealiasing algorithm. Overall, there is one-fourth the number of dealiasing errors in the 2DVDA products over the legacy VDA products (17 vs. 70). The legacy VDA average error rate is ~0.72% and the 2DVDA average error rate is ~0.18%. The number of products with errors and the average error rates are exceedingly small for the CD elevation cuts due, primarily, to our method of evaluation. Although, there was generally little return in the higher elevation cuts, large-scale images of the velocity products show dealiasing artifacts due to side lobe contamination.

We also looked at the frequency of errors by radar site. Table 5 shows the number of products by site for split, batch, and CD cuts. (Refer to Figure 1 for the number of volume scans of each type of VCP for each site.) The site with the fewest products examined was KMLB (748) while the site with the largest number of products examined was KLWX (5644); the average number of products per site was about 3400. Some factors that limited the number of products examined from each site included distance of Hurricane Irene from a radar, use of VCP 121, and the use of sectorized PRFs.

For split cuts (Table 6) the frequency of velocity dealiasing errors between the ½ deg super-resolution and 1 deg resolution products using the legacy VDA is roughly comparable and proportional to the number of products analyzed. Although the 2DVDA had consistently fewer dealiasing errors for all the sites than the legacy VDA, it had a somewhat higher frequency of errors for the 1 deg resolution products for KLTX (23 errors) and KOKX (25 errors) compared to the other sites. KLTX velocity products exhibited small errors in fragmented eye-wall bands. For KOKX, ground clutter artifacts were occasionally large enough to be seen in a full-range product. These were mainly speckles of velocities placed in the wrong Nyquist co-interval ($2V_N$). In the batch cuts, the number of legacy VDA errors for KMHX stands out. These errors occur mostly as wedges within the ground clutter preceding the onset of the outer bands or in isolated patches at the farthest range of the velocity product. The CD cuts had few errors for either algorithm (21 for VDA and 12 for 2DVDA). The nature of the errors was similar to those seen in the batch cuts near the radar. That is, wedge-shaped errors were present in the VDA products while small side-lobe contaminated errors were present in the 2DVDA products. While much better than the legacy VDA, the 2DVDA is not perfect.

6. DISCUSSION AND EXAMPLES

Both WBJ09 and LT10 included weather events other than hurricanes in their studies. Besides velocity products from Hurricane Ike (2008), WBJ09 evaluated frontal boundaries in clear air (VCP 31), a squall line with super cells, and general thunderstorms. LT10 evaluated velocity products containing tornadic and/or mesocyclones signatures, squall lines, and gust fronts. Both studies concluded that the 2DVDA was superior to the legacy VDA in reducing velocity dealiasing errors for all types of weather events examined.

Of particular interest was the performance of the 2DVDA on Hurricane Irene in contrast to the performance observed by LT10. LT10 analyzed 201 velocity products with 1 deg azimuthal resolution at 0.5 deg elevation for hurricanes Rita (2005), Gustav (2008), and Ike (2008). They found the legacy VDA had 185 dealiasing errors while the 2DVDA had only five dealiasing errors. (Their results are summarized in Table 7.) Note that in their analysis a velocity product could have more than one error if the errors were non-contiguous. The corresponding number of errors for each technique for Hurricane Irene from Table 3 shows that the legacy VDA had 286 products with dealiasing errors while the 2DVDA had 26 products with dealiasing errors.

Also striking, was the difference in the number of legacy VDA products with large errors. LT10 tabulated 24 large errors (personal communication). By contrast, for Hurricane Irene we saw only two legacy VDA-dealiased velocity products with a large dealiasing error. In both our study and the earlier LT10 study, the 2DVDA had no large dealiasing errors. Figure 2 shows an example of a large VDA dealiasing error seen at KOKX for Hurricane Irene. Figure 3 shows another example of a large velocity dealiasing error produced by the legacy VDA seen at KAKQ. These dealiasing errors are like those seen by LT10. LT10 counted 26 medium-sized errors for the legacy VDA and no medium-sized errors for the 2DVDA. For the legacy VDA, we observed 16 medium-sized errors with Hurricane Irene, nine from KAKQ and seven from KLTX. For the 2DVDA we observed just one medium-sized from KLTX. Figure 4 shows a comparison of the velocity products from KLTX for the legacy VDA and the 2DVDA which had the medium-sized error which was the largest dealiasing error we saw for the 2DVDA. In this instance, the legacy VDA had no trouble dealiasing the band near the eye.

The improved performance of the 2DVDA over the legacy VDA is not as pronounced for Hurricane Irene as it was for the three hurricanes analyzed by LT10. From the National Hurricane Center's Tropical Cyclone Reports [available online at http://www.nhc.noaa.gov/pastall.shtml#tcr] we surmise Irene was not as strong as the other hurricanes when it made landfall. Also, Irene had an extensive rain shield ahead of it. That is, for the times periods we analyzed, there were few gaps in echo coverage along radials between the rain bands. Thus, Irene was more easily dealiased by the legacy VDA. Irene traveled parallel to and at some distance from the radars as it traveled up Florida's east coast. Later, Irene moved obliquely towards the radars upon initial landfall and only directly towards the radars after it had weakened. By contrast, the three hurricanes examined by LT10 were stronger and moved directly towards the radars during the periods they analyzed.

7. SUMMARY

The new two-dimensional velocity dealiasing algorithm (2DVDA), slated for deployment starting in the fall of 2012, clearly reduced the frequency and severity of velocity dealiasing errors over the legacy VDA for Hurricane Irene. This study supports the conclusions of both WBJ09 and LT10 that the 2DVDA is superior to the legacy VDA. At low elevation angles there was an order of magnitude reduction in the frequency of velocity dealiasing errors. At higher elevation angles the reduction in dealiasing errors was not as pronounced but the likelihood of having a dealiasing error is much lower to begin with.

There are two conditions under which the 2DVDA cannot be used: 1) a site uses different PRFs in a scan; 2) a site chooses to use VCP121 and the MPDA. Sites will have the option of not using the 2DVDA if they so choose.

8. ACKNOWLEDGMENTS

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VCPs	Split Cuts			Batch Cuts						Contiguous Doppler Cuts				
12/212	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°	19.5°
21/221	0.5°		1.45°		2.4°	3.35°	4.3°		6.0°		9.9°		14.6°	19.5°

Table 1. Pairing of elevation angles between the VCPs to facilitate statistical analysis

		½ Deg Super Resolution Split Cuts							
		Legacy VDA Error Count				2DVDA Error Count			
VCP	# of Vols	0.5°	0.9°	1.3/1.45°	Total	0.5°	0.9°	1.3/1.45°	Total
21/221	219	20	-	13	33	1	-	1	2
12/212	1471	286	180	82	548	19	13	7	39
Total	1690	306	180	95	581	20	13	8	41

Table 2. Number of velocity products with errors for the legacy VDA and the 2DVDA for ½ deg azimuthal resolution split cuts by elevation for Hurricane Irene.

		1 Deg Resolution Split Cuts							
		Legacy VDA Error Count				2DVDA Error Count			
VCP	# of Vols	0.5°	0.9°	1.3/1.45°	Total	0.5°	0.9°	1.3/1.45°	Total
21/221	219	17	-	10	27	0	-	0	0
12/212	1471	269	161	85	515	26	21	15	62
Total	1690	286	161	95	542	26	21	15	62

Table 3. Number of velocity products with errors for the legacy VDA and the 2DVDA for 1 deg azimuthal resolution split cuts by elevation for Hurricane Irene.

		Error Count: Legacy VDA / *2DVDA*						
Batch	Elevation cut	1.8°	2.4°	3.35°/3.1°	4.3°/4.0°	5.1°	6.0°/6.4°	**Total**
Batch	Error Count	25 / *10*	31 / *6*	7 / *1*	3 / *0*	4 / *0*	0 / *0*	70 / *17*
CD	Elevation cut	8.0°	9.9°/10.0°	12.5°	14.6/15.6°	19.5°	-	**Total**
CD	Error Count	4 / *1*	3 / *2*	4 / *1*	7 / *4*	3 / *0*	-	21 / *8*

Table 4. Number of velocity products with errors by elevation angle and waveform for Hurricane Irene. Each “Error Count” cell in the table shows the number of legacy VDA products with errors followed by the number of 2DVDA products with errors.

Site	KAMX	KMLB	KCLX	KLTX	KMHX	KAKQ	KLWX	KOKX	Total
# of Split Products	950	272	1374	1254	872	1602	1992	1386	**9702**
# of Batch Products	950	272	1374	1254	872	1602	1992	1386	**9702**
# of CD Products	767	204	1145	1045	701	1335	1660	1155	**8012**
Total # of Products	**2667**	**748**	**3893**	**3553**	**2445**	**4539**	**5644**	**3927**	**27416**

Table 5. Number of products examined by site and by waveform (split, batch, and CD) for Hurricane Irene. Split cuts include both ½ deg and 1 deg azimuthal resolution products.

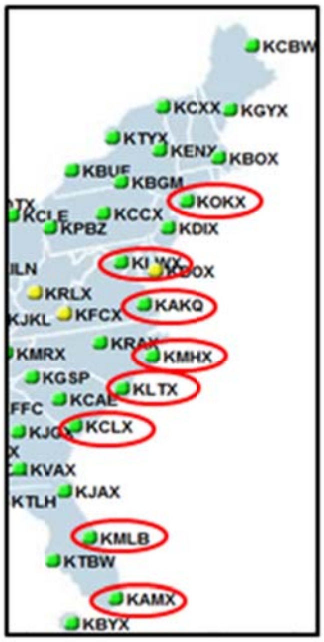
Error Count: Legacy VDA / *2DVDA*								
	KAMX	**KMLB**	**KCLX**	**KLTX**	**KMHX**	**KAKQ**	**KLWX**	**KOKX**
½° Res Split Cuts	27 / *1*	17 / *1*	53 / *11*	116 / *15*	41 / *1*	125 / *0*	77 / *2*	125 / *10*
1° Res Split Cuts	36 / *2*	14 / *0*	67 / *7*	105 / *23*	42 / *0*	139 / *1*	63 / *4*	76 / *25*
Batch Cuts	0 / *0*	1 / *0*	5 / *0*	6 / *6*	22 / *0*	17 / *3*	2 / *2*	11 / *3*
CD Cuts	0 / *0*	0 / *0*	9 / *0*	0 / *0*	4 / *0*	0 / *0*	0 / *0*	8 / *8*

Table 6. Number of velocity products with errors by WSR-88D site and by waveform. Each cell in the table shows the number of legacy VDA products with errors followed by the number of 2DVDA products with errors.

	Hurricane		
	Rita – 9/24/2005	**Gustav – 9/1/2008**	**Ike – 9/13/2008**
Site **WSR-88D**	Lake Charles, LA KLCH	Slidell, LA KLIX	Houston, TX KHGX
# of Products	62	39	100
Error Count **VDA/2DVDA**	42 / 4	37 / 0	106/ 1
VDA Error Size	0 Lge; 2 Med; 40 Sm	6 Lge, 8 Med; 23 Sm	18 Lge; 16 Med; 72 Sm
2DVDA Error Size	0 Lge; 0 Med; 4 Sm	0 Lge; 0 Med; 0 Sm	0 Lge; 0 Med; 1 Sm

Table 7. Summary of error counts and sizes for legacy VDA and 2DVDA for three hurricanes from LT10.

8 Sites Used in Hurricane Irene Velocity Dealiasing Analysis



Sites Used in Analysis
Upton, NY – KOKX
Sterling, VA – KLWX
Wakefield, VA – KAKQ
Morehead City, NC – KMHX
Wilmington, NC – KLTX
Charleston, SC – KCLX
Melbourne, FL – KMLB
Miami, FL – KAMX

	No. of Volumes		
Site	**12/212**	**21/221**	**Total**
KAMX	109	74	183
KMLB	0	68	68
KCLX	229	0	229
KLTX	209	0	209
KMHX	94	77	171
KAKQ	267	0	267
KLWX	332	0	332
KOKX	231	0	231
Total	**1471**	**219**	**1690**

Figure 1. Geographical depiction of WSR-88D sites used in the Hurricane Irene study. Also shown is a table of the number of volume scans of data analyzed from each site for VCPs 21/221 and 12/212.

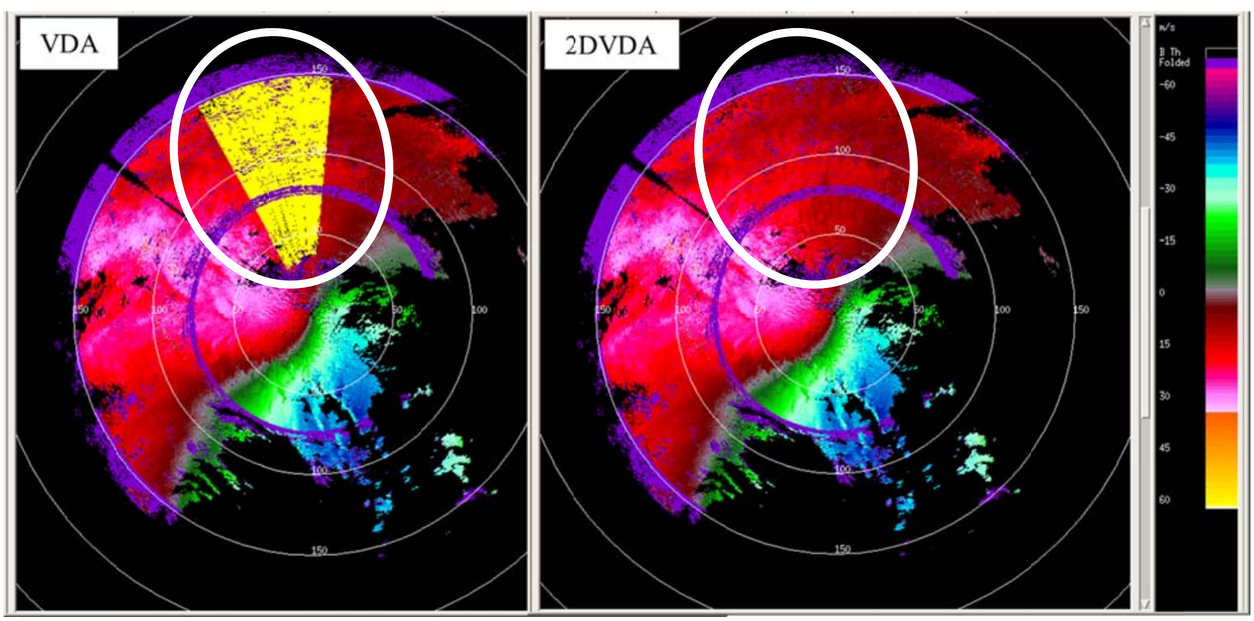


Figure 2. Hurricane Irene August 28, 2012 from Upton, NY WSR-88D (KOKX) at 07:21Z at 0.5 deg elevation. Circulation center is 150 n mi south-southwest of radar. Legacy VDA dealiased ½ deg azimuthal resolution velocity product is on the left, the 2DVDA dealiased product is on the right. Note large yellow wedge of incorrectly dealiased velocities for the legacy VDA (see white ovals). Range rings are every 50 n mi.

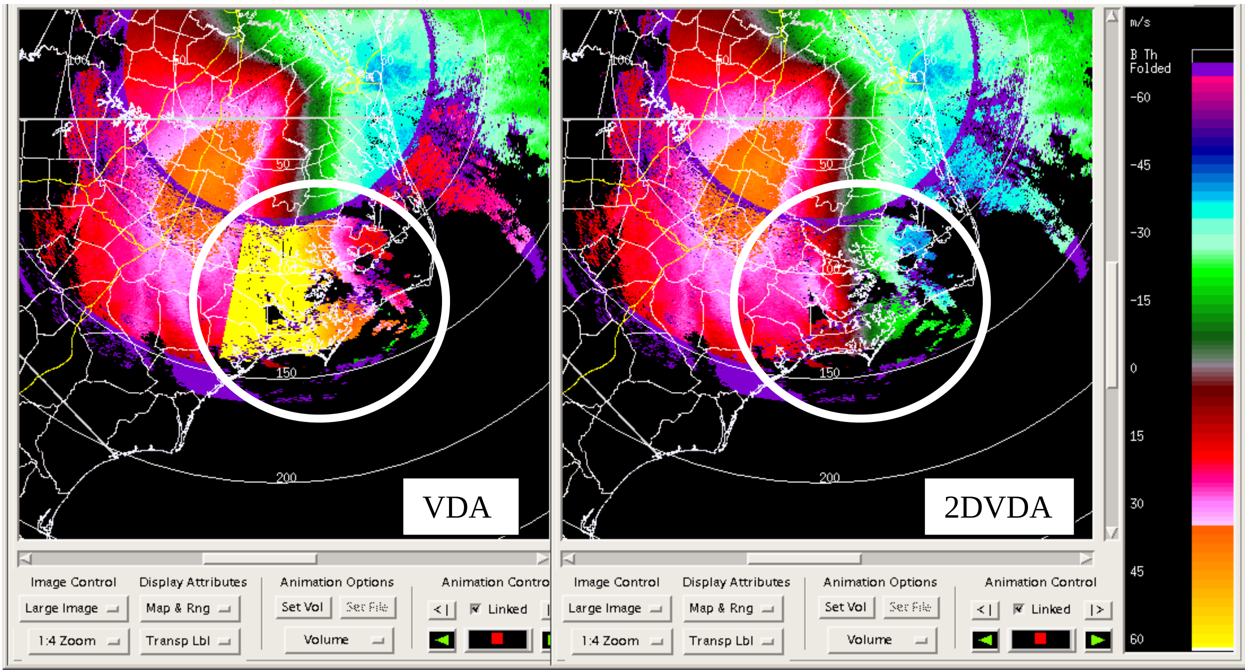


Figure 3. Hurricane Irene August 27, 2011 from Wakefield, VA WSR-88D (KAKQ) at 15:23Z at 0.5 deg elevation. Circulation center is about 115 n mi south of the radar. The legacy VDA dealiased ½ deg azimuthal resolution product is on the left; the 2DVDA dealiased product is on the right. Note large yellow area south of radar in second trip for the legacy VDA that is incorrectly dealiased (see white circles). Range rings are every 50 n mi.

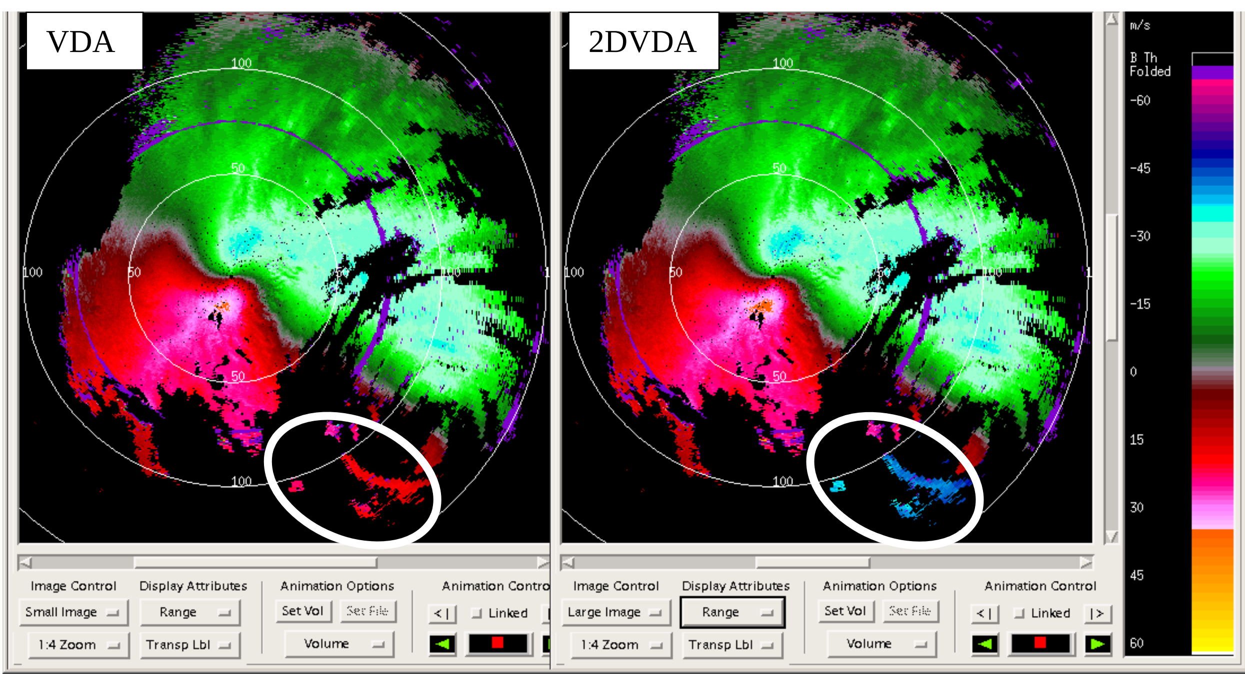


Figure 4. Hurricane Irene August 27, 2011 from Wilmington, NC (KLTX) at 04:05Z at 1.3 deg elevation. Circulation center is about 125 n mi southeast of the radar. The legacy VDA dealiased 1 deg resolution product is on the left; the 2DVDA dealiased product is on the right. Note the blue inbound incorrectly dealiased fragmented eye wall in the 2DVDA panel (see white ovals). Range rings are every 50 n mi.