P2.9 **COMBINED WSR-88D TECHNIQUE TO REDUCE RANGE ALIASING USING PHASE CODING AND MULTIPLE DOPPLER SCANS**

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1. INTRODUCTION

Since fielding the Weather Service Radar 1988 Doppler (WSR-88D) system in the early 1990's, the NEXRAD Program has recognized range aliasing (folding) as a major weakness. To reduce range folding using a uniformly pulsed radar such as the WSR-88D, one can lower the pulse rate but in so doing will increase the likelihood of introducing aliased velocities (Doviak and Zrnić, 1984). A practical trade-off is to keep unambiguous velocities above 20 m s^{-1} and accept some range folding. As late as 1999 the NEXRAD Technical Advisory Committee deemed system performance as the second highest technical need to be addressed in the WSR-88D system. Mitigation of range aliasing was specifically cited.

Since the mid 1990's, the NEXRAD Program has sponsored a two-pronged effort to reduce range folding. The first approach, called the short-term "software" solution, uses multiple Doppler scans to reduce range folding. Fielded in 2004, this technique is called the Multiple Pulse Repetition Frequency (PRF) Dealiasing Algorithm (MPDA) (Conway et al., 1997). MPDA processing is done in the WSR-88D's Radar Product Generator (RPG). The second approach, termed the long-term "hardware" solution relies on advanced signal processing at the WSR-88D's Radar Data Acquisition (RDA) unit. In fact, two hardware approaches have been pursued: phase coding and staggered Pulse Repetition Time (PRT). Of the two, the WSR-88D Radar Operations Center (ROC) Engineering Branch deemed the phase coding technique (Sachidananda and Zrnić, 1999), hereafter referred to as the SZ-2 algorithm, as better suited for elevation angles at or below 1.5 degrees where both range folding and ground clutter contamination are most likely to occur. The SZ-2 algorithm was operationally deployed in 2007. Both the SZ-2 algorithm and the MPDA have residual range folding that can obscure important velocity information. The purpose of this paper is to show that SZ-2 and MPDA complement each other and can be combined to reduce range folding to trivial amounts within 230 km.

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2. WSR-88D SCANNING STRATEGIES

Scanning strategies in the WSR-88D System are referred to as Volume Coverage Patterns (VCPs). Dr. Nolan Atkins (Lyndon State College) succinctly defines a VCP as a predefined series of 360 degree sweeps of the antenna at selected elevation angles completed in a specified period of time. Seven VCPs, 11, 12, 21, 121, 211, 212, and 221, are designed for precipitating events. The VCPs provide different benefits through different scanning strategies or signal processing techniques. They differ in completion times and vertical spacing between elevation angles. All sample the atmosphere from 0.5 degrees to 19.5 degrees and provide reflectivity data to 460 km in range and Doppler velocity and spectrum width data to 230 km in range through a depth of 21 km. Data resolution is one degree azimuthally by 0.25 km in range for velocity and spectrum width data and one degree azimuthally by one km in range for reflectivity data. (Super resolution will be available at the lowest elevation angles with a new software release in the spring of 2008. Doppler data will be extended to a range of 300 km. Reflectivity data will have 0.25 km resolution. Both reflectivity and Doppler data will have 0.5 deg resolution.) VCPs 11 and 211 collect data in 5 minutes at 14 unique elevation angles. VCPs 21, 121, and 221 collect data in about 6 minutes at 9 unique elevation angles. VCPs 12 and 212 collect data at 14 unique elevation angles in about 4 min 30 sec with closely-spaced vertical separation of low elevation angles. VCPs 211, 212, and 221 use the SZ-2 algorithm. All precipitation VCPs use a separate scan to obtain long range surveillance reflectivity data at elevation angles at or below 1.5 degrees elevation which is followed by one or more Doppler scans to obtain velocity and spectrum width data. The surveillance scan, which uses a low PRF, minimizes range folding by maximizing the unambiguous range. Doppler scans, at high PRFs, reduce velocity aliasing by maximizing the unambiguous velocity. Information from the surveillance scan is used to help place the range-folded velocities from the Doppler scan. At mid-elevation angles (2.4 to 6.0 deg) a batch waveform is used. For each radial of data this waveform sends out a few pulses for surveillance coverage followed by tens of pulses to obtain the Doppler moments. At higher elevations (> 6.0 deg) Doppler scans provide both reflectivity and Doppler data.

The WSR-88D System uses eight PRFs. The lowest three PRFs are used for long-range surveillance while the highest five are used to obtain Doppler velocity and spectrum width estimates. Table 1 lists the PRFs and associated values for unambiguous velocity and range. A concise summary of VCPs may be found at http://www.wdtb.noaa.gov/buildTraining/Build9/pdfs/VCP_Comp_Table.pdf. A more extensive discussion of VCPs is provided in the Federal Meteorological Handbook No. 11, Doppler Radar Meteorological Observations, Part C, WSR-88D Products and Algorithms, April 2006.

3. MULTIPLE-PRF DEALIASING ALGORITHM (MPDA)

The MPDA mitigates range folding by combining Doppler data from up to three scans at the same elevation angle but where each scan uses a different PRF. Changing the PRF changes the unambiguous range and thus the areas that may be range folded. The primary PRFs used are ~1282, ~1095, and ~857 Hz with unambiguous ranges of 117 km, 137 km, and 175 km, respectively. In the WSR-88D System they are referred to simply as PRFs 8, 6, and 4, respectively. Experience has shown the MPDA works well out to about 175 km but is inconsistent in reducing range folding beyond this range.

Another feature of the MPDA is its approach to velocity dealiasing. MPDA takes advantage of having up to three independent measurements of velocity for the same location in space. It first tries to dealias all locations for which there are three velocities. If no satisfactory solution is found with three velocities, it will next try to dealias using pairs of velocities. Some locations will only have two velocities because the third velocity is range folded. Finally, MPDA completes its processing by dealiasing velocities for locations for which only one velocity is available. While the use of multiple velocity estimates generally improves the reliability of dealiasing, a region with only velocity data from the scan using PRF 4 may have dealiasing errors because its Nyquist velocity is only about 21 m s^{-1}. An in-depth discussion of the MPDA processing logic is provided by Zittel and Wiegman (2005) at: http://www.roc.noaa.gov/news/NNwinter05d.pdf. VCP 121, used with the MPDA, samples nine unique elevation angles (0.5, 1.5, 2.4, 3.4, 4.3, 6.0, 9.9, 14.6, 19.5 deg) in 5 min 30 sec. MPDA runs on the lowest 5 elevation angles; the legacy Velocity Dealiasing Algorithm (VDA) is used at elevation angles at six degrees and higher.

4. SZ-2 ALGORITHM

The SZ-2 algorithm reduces range folding by recovering weak trip signal embedded within strong trip signal. To separate out the weak trip from the strong trip signal, SZ-2 uses a sequence of 32 unique phases to change the transmitted phase of each succeeding radar pulse, which results in eight modulation phases for any overlaid signal allowing for overlaid signal separation. (Sixty-four pulses are used per radial to reduce the variance of the estimate.) Use of a high PRF such as PRF 8 mitigates velocity dealiasing errors. Because of the possibility of signal contribution from third and fourth trip echo when using a high PRF, SZ-2 uses a low PRF surveillance scan to assign energy to the appropriate trip similar to the other VCPs deployed in the WSR-88D. The SZ-2 processing is only applied to elevation angles less than 1.65 degrees. This algorithm works well at far ranges but leaves a band of range-folded signal at the start of the second trip where overlaid clutter signal obscures the second trip signal. Current VCP definitions limit SZ-2 to one PRF. (SZ-2 implementation can use any PRF but a limitation of the RPG does not permit changing the rotation rate for a given VCP when a different PRF is required while still maintaining 64 pulses per one degree radial.) To shift where the band of range folding occurs, three new VCPs provide diversity where the band of range folding occurs. VCP 211 uses PRF 8, VCP 212 uses PRF 6, and VCP 221 uses PRF 5. Finally, while significantly mitigating range folding, SZ-2 still has some velocity aliasing requiring a velocity dealiasing algorithm at the RPG. Zrnić et al., 2006 provide details of the SZ-2 implementation in the WSR-88D.

5. COMBINING SZ-2 AND MPDA IN VCP 121

Because the SZ-2 algorithm runs in the SIGMET RVP8 processor, which is part of the RDA system, while the MPDA runs in the Radar Product Generator (RPG) Linux work station, the two techniques are readily combined. (For simplicity the combined technique is referred to as the enhanced VCP 121.) The SZ-2 algorithm range unfolds velocity data for the first Doppler scan on a radial-by-radial basis at the RDA which transfers each radial to the RPG. The extra Doppler scans are range unfolded using legacy range unfolding logic. At the RPG the MPDA replaces the residual range-folded data in the SZ-2 Doppler scan using data from the extra scans and performs velocity dealiasing as described above. To match the MPDA requirement of using PRF 8 for the first Doppler cut, the enhanced VCP 121 uses the specifications for VCP 211 which also uses PRF 8. To accommodate the SZ-2 processing, which requires 64 pulses (43 pulses are used in the baseline VCP 121), the enhanced VCP 121 antenna rotation rate is slowed to the VCP 211 rate for the first Doppler scan at both 0.5 and 1.45 degrees elevation. Also, the number of surveillance pulses was increased from 15 to 17 to match VCP 211. The slower rotation rates add about 15 seconds to the total volume scan time for the enhanced VCP 121 for an estimated completion time of 5 min 45 sec. Table 2 compares the baseline to the enhanced VCP 121. The italicized bold text shows where the enhanced VCP 121 differs from the baseline VCP 121 at the 0.5 and 1.5 deg elevation angles. One change to VCP 121 not related to adding SZ-2 is that the RDA now does range unfolding of the extra Doppler scans at 0.5 and 1.5 degrees to support super resolution data processing. Previously those scans were range unfolded at the RPG. Use of the term “contiguous” in Table 2 merely indicates the transmitted pulses are uniformly spaced in time.

6. STATISTICAL ANALYSES

6.1 *Methodology*

To show the improvement in range folding reduction provided by the enhanced VCP 121, we compare its volume of range-folded data to the volume of range-folded data using SZ-2 by itself. To obtain the volume of range folded from the SZ-2 algorithm alone, we modify the MPDA code slightly to ignore the extra Doppler scans and use just the first Doppler scan at each elevation. The data mimic what would be presented by using SZ-2 alone. We compute the areal volume of data that is either range-folded or velocity and then compute the ratio of the velocity data to the combined velocity and range-folded data. Multiplying by 100 gives the percentage of the total coverage that is velocity data:

$$Pct(VE) = 100 * \frac{\sum_{m=1}^{N} Area(VE)_m}{\sum_{m=1}^{N} Area(RF)_m + \sum_{m=1}^{N} Area(VE)_m}$$

where *N* is the number of volume scans in a data case and *m* is an individual volume scan. *RF* is range-folded data and *VE* is velocity data. Subtracting the percent that is velocity data from 100 yields the percent of the field that is range folded formulated as:

$$Pct(RF) = 100 - Pct(VE)\,.$$

It is important to note the analyses were performed on velocity products whose coverage extends only to 230 km. Super resolution velocity products, which extend to 300 km, will have considerably more range folding regardless of VCP being used. Although statistics were computed for both 0.5 and 1.5 deg elevation, only the results for the lowest elevation scan are presented. This is where range folding is most problematic.

6.2 *Initial Results*

Level 2 Archive data for four data cases with widespread precipitation were collected on the ROC's test bed WSR-88D (KCRI) during the fall and winter of CY 2006. Level 2 Archive data were also obtained from the National Climatic Data Center for the nearby Norman Forecast Office’s WSR-88D (KTLX) which used the standard baseline VCPs 11, 12, 21, and 121. (KTLX is located about 18 km east-northeast of KCRI.) The data were played back through non–operational RPGs at the ROC. Table 3 lists the cases, the weather event, the number of hours analyzed, and compares the percent of velocity data obtained from the enhanced VCP 121, SZ-2 used alone, and KTLX. The average of the four cases shows the enhanced VCP 121 provides velocity data for slightly over 98 percent of the field. Use of SZ-2 by itself provides velocity data for nearly 91 percent of the data field. The average for the baseline VCPs provided slightly less than 58 percent. For the fourth case on 29-30 December, KTLX was operating in the baseline VCP 121. For this case the baseline VCP 121 provided velocity data for only about 63 percent. For the other three cases which used VCPs 11, 12, and 21, the KTLX radar's RPG automatically selected which PRF to use. When the RPG is in "Auto PRF" mode, PRF 4, which usually provides the least volume of range-folded data for VCPs 11, 12, and 21, will not be selected. Only PRFs 5, 6, 7, or 8 will be used.

6.3 *Field Test Results*

To obtain geographic and meteorological diversity, the ROC conducted a field test with the enhanced VCP 121 at eight NWS offices with operational WSR-88Ds during the latter half of CY 2007. Sites participating in the test were Billings, MT (KBLX), Boise, ID (KCBX), Goodland, KS (KGLD), Lake Charles, LA (KLCH), Lincoln, IL (KILX), Melbourne, FL (KMLB), San Juan, PR (TJUA), and Tallahassee, FL (KTLH). Through early December these sites logged over 1500 hours using the enhanced VCP 121. Additionally, the ROC's test bed WSR-88D collected data using the enhanced VCP 121 during the test period. Eight cases of interest were chosen for analysis as shown in Table 4. Because most WSR-88D sites are widely spaced, no statistical comparisons were made between sites using the enhanced VCP 121 and sites using baseline VCPs. Instead, the comparisons were restricted to the enhanced VCP 121 and SZ-2 by itself. Use of just the SZ-2 data yields slightly less than 89 percent velocity data, while use of the enhanced VCP 121 provides slightly more than 97 percent velocity data.

For both the enhanced VCP 121 and the SZ-2 used alone, the average volume of velocity data obtained during the field test is slightly lower than that obtained from the preliminary data sets. The corollary is that there were more range-folded data in the field test data sets. Because some of the field site data sets contained extensive coverage beyond second trip, data closer to the radar were range folded. Also, some sites chose to apply clutter filtering on all bins rather than use a bypass map to identify ground targets on which to do clutter filtering. Clutter filtering on all bins degrades the performance of the SZ-2 algorithm slightly.

7. EXAMPLES

Two examples are shown. The first, 29-30 December 2006 is drawn from the original set of four cases from KCRI and the KTLX WSR-88Ds. The second case is from Lake Charles, LA, one of eight WSR-88D operational sites that participated in a field test of the enhanced VCP 121.

7.1 *Winter Storm Case*

Between December 29 and 31, 2006, during a major winter storm, up to 18 inches of snow fell in the Oklahoma panhandle and up to 4 inches of rain fell in southeastern Oklahoma. During this period KCRI collected Level 2 Archive data using the enhanced VCP 121. For several hours on December 29-30, 2006 the Norman forecast office collected similar data using the baseline VCP 121 on KTLX. Figure 1a shows a side-by-side comparison of the reflectivity from KCRI and KTLX collected about 02Z on December 30th. The overall patterns match quite well. Minor differences would be expected due to differences in beam propagation. Figure 1b shows a side-by-side comparison of the corresponding velocity products. The velocity product from KTLX shows extensive range folding beyond 175 km while the velocity product from KCRI has almost no range folding. Figure 1c shows what the KCRI velocity product would have looked like had the radar been operating with just SZ-2. A band of range folding is clearly seen at the start of second trip about 117 km.

7.2 *Tropical Cyclone Case*

On September 12, 2007 Tropical Storm Humberto formed about 154 km south-southwest of Galveston, TX. It intensified as it first moved northward and then turned to the north-northeast. On September 13th, it became a hurricane just off the Texas coast near High Island and made landfall about 07Z at its peak intensity with winds about 44 m s^{-1}. Figure 2a shows a side-by-side comparison of reflectivity images from the Houston, TX WSR-88D (KHGX) and the Lake

Charles, LA WSR-88D (KLCH) about 07Z. At this time the eye was about 80 km east-northeast of KHGX and about 120 km west-southwest of KLCH. KHGX was operating with the baseline VCP 121 while KLCH was operating with the enhanced VCP 121. Although the images match well, KHGX is already starting to overshoot outer bands east of the eye. Figure 2b shows side-by-side velocity images from KHGX and KLCH. Note that the KHGX velocities around the eye are partially obscured by range-folded signal while the velocities in the KLCH image are free of range-folded signal. As in the winter storm case, extensive range folding occurs beyond 175 km for KHGX using the baseline VCP 121. Figure 2c shows what the KLCH velocity image would have looked like had the radar been operating with just SZ-2. A band of range-folded signal encircles the radar and obscures part of the eye structure. Other areas appear noisier than the enhanced VCP 121 in Figure 2b.

8. SUMMARY AND FOLLOW-ON WORK

The merging of two separate techniques, SZ-2 and MPDA, to reduce range folding has been shown to be easily accomplished within the baseline VCP 121. The inclusion of SZ-2 removes nearly all range folding left beyond 175 km by the MPDA while the MPDA removes the band of range folding left by SZ-2 at the start of second trip. Residual range folding within 230 km can be attributed primarily to strong third and fourth trip echo. Because the enhanced VCP 121 requires an extra 15 seconds to complete a volume scan, Crauder and Zittel (2008) conducted a companion study to determine the feasibility of omitting the middle PRF 6 scan which would save about 30 seconds. The results show only a slight decrease in the volume of velocity data. Velocity data filled in by the MPDA are slightly smoother.

9. ACKNOWLEDGMENTS

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REFERENCES

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) submitted.

Doviak, R.J. and D.S. Zrnić, 1984: *Doppler Radar and Weather Observations*. Academic Press, Inc., 458 pp.

Federal Meteorological Handbook No. 11, Doppler Radar Meteorological Observations, Part C, WSR-88D Products and Algorithms, April 2006.

Sachidananda, M. and D.S. Zrnić, 1999: Systematic Phase Codes for Resolving Range Overlaid Signals in a Doppler Weather Radar. *J. Atmos. Oceanic Technol.*, **16**, 1351-1363.

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

Zrnić, D., S. Torres, J. Hubbert, G. Meymaris, S. Ellis, and M. Dixon, 2006: NEXRAD Range-Velocity Ambiguity Mitigation, SZ-2 Algorithm Recommendation. WSR-88D Radar Operation Center Engineering Branch Publication.

PRF Number	1	2	3	4	5	6	7	8
PRF (Hz)	322	446	644	857	101 4	109 5	118 1	128 2
R_a (km)	466	336	233	175	148	137	127	117
V_a (m s^{-1})	8	11	16	21	25	27	30	32

Table 1. Eight PRFs are used by the WSR-88D system. R_a is unambiguous range; V_a is unambiguous velocity.

	Baseline VCP 121			Enhanced VCP 121	
Elev.	Waveform	No. of Pulses	PRF No.	Waveform	No. of Pulses
0.5	CS	15	1	***CS/SZ2***	***17***
0.5	CD/W	43	8	***CD/SZ2***	***64***
0.5	CD/WO	40	6	***CD/W***	40
0.5	CD/WO	40	4	***CD/W***	40
1.5	CS	15	1	***CS/SZ2***	***17***
1.5	CD/W	43	8	***CD/SZ2***	***64***
1.5	CD/WO	40	6	***CD/W***	40
1.5	CD/WO	40	4	***CD/W***	40
2.4	B	6,40	1,8	B	6,40
2.4	CD/WO	40	6	CD/WO	40
2.4	CD/WO	40	4	CD/WO	40
3.4	B	6,40	2,8	B	6,40
3.4	CD/WO	40	6	CD/WO	40
3.4	CD/WO	40	4	CD/WO	40
4.3	B	6,40	2,4	B	6,40
4.3	CD/WO	40	7	CD/WO	40
6.0	B	6,40	3,5	B	6,40
9.9	CD/WO	40	7	CD/WO	40
14.6	CD/WO	43	8	CD/WO	43
19.5	CD/WO	43	8	CD/WO	43

Table 2. Comparison of baseline VCP 121 to the enhanced VCP 121. CS=Contiguous Surveillance waveform, CD/W=Contiguous Doppler waveform with range unfolding done at the RDA, CD/WO=Contiguous Doppler waveform with no range unfolding, B=Batch waveform. Note there are two entries for the number of pulses and the PRF number for scans that use a batch waveform. The first number refers to the surveillance portion while the second numbers refer to the Doppler portion of this waveform.

		Percent Velocity Data			
Case	**No. of Hours**	**KCRI Enhanced VCP 121**	**KCRI SZ-2 Only**	**KTLX Legacy VCP**	**Weather Event**
10-Oct-06	7	97.10	87.46	61.27	Widespread rain in sourthern and central Oklahoma
15-Oct-06	5	98.75	92.28	45.84	Heavy rain in southern and central Oklahoma
6-Nov-06	8	98.29	91.37	61.68	Hail storms in Oklahoma, straight line wind damage in Gainesville, TX
30-Dec-06	8	98.04	91.22	63.10	Blizzard in Oklahoma Panhandle, heavy rain southeastern Oklahoma
Average		**98.05**	**90.58**	**57.97**	

Table 3. Summary of initial four cases showing percent of velocity data obtained from the enhanced VCP 121, SZ-2 only, and baseline (legacy) VCPs at 0.5 deg elevation.

		Percent Velocity Data			
Site	**Case**	**No. of Hours**	**Enhanced VCP 121**	**SZ-2 Only**	**Weather Event**
KCRI	20-Jun-07	12	95.28	90.18	Severe storms embedded in squall line
KLCH	13-Sep-07	24	96.90	88.03	Hurricane Humberto
KCRI	19-Aug-07	9	98.16	88.77	Sub-tropical storm Erin
KBLX	5-Oct-07	11	97.33	89.89	Stratiform rain with strong winds
KTLH	21-Sep-07	21	98.22	91.34	Tropical Depression Ten
KILX	27-Oct-07	22	97.63	83.25	Stratiform rain with strong winds
KCBX	20-Oct-07	18	96.29	85.10	Stratiform rain with strong winds
TJUA	26-Oct-07	12	98.26	93.21	Area of Disturbance prior to Hurricane Noel
	Average		**97.26**	**88.72**	

Table 4. Summary of eight cases analyzed from field test showing percent of velocity data obtained from the enhanced VCP 121 and for SZ-2 only at 0.5 deg. elevation.

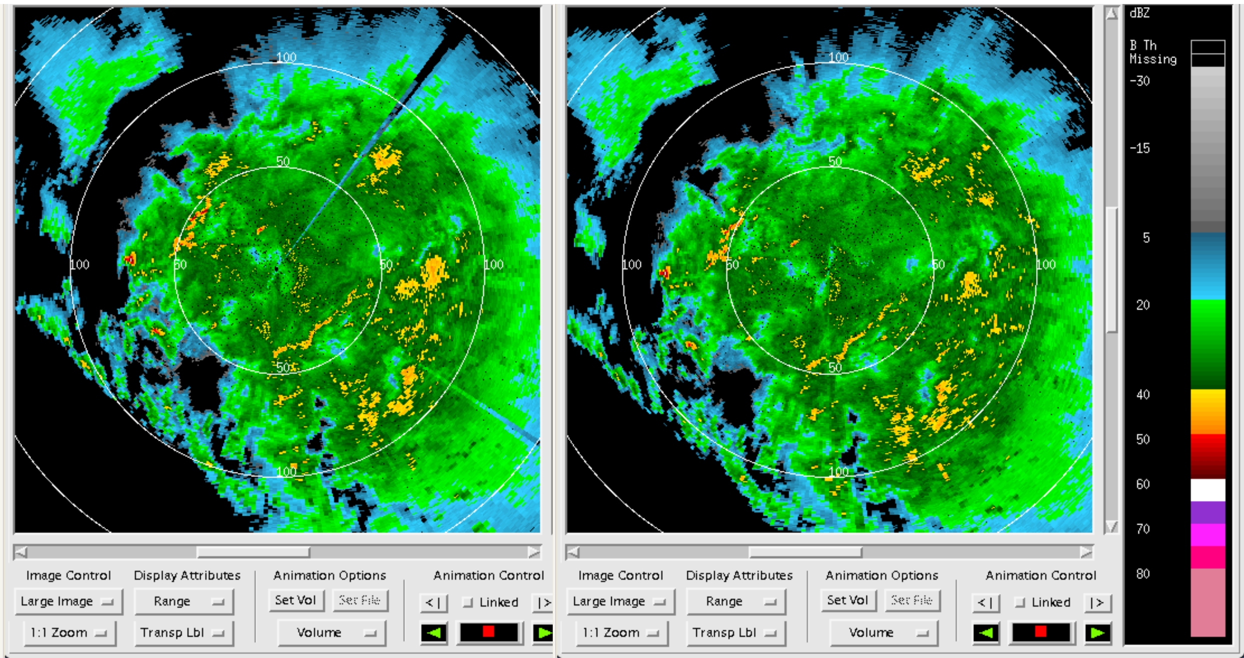

Figure 1a. Side-by-side comparison of reflectivity image from KCRI (left) and KTLX (right) for December 30, 2006 around 02Z. Beam blockage in the northeast and southeast quadrants due to towers is evident in the KCRI image. Coverage and overall intensity are similar. Yellow colors show areas of heavier precipitation. KTLX is located about 18 km (10 n mi) east-northeast of KCRI. Range rings are every 93 km (50 n mi).

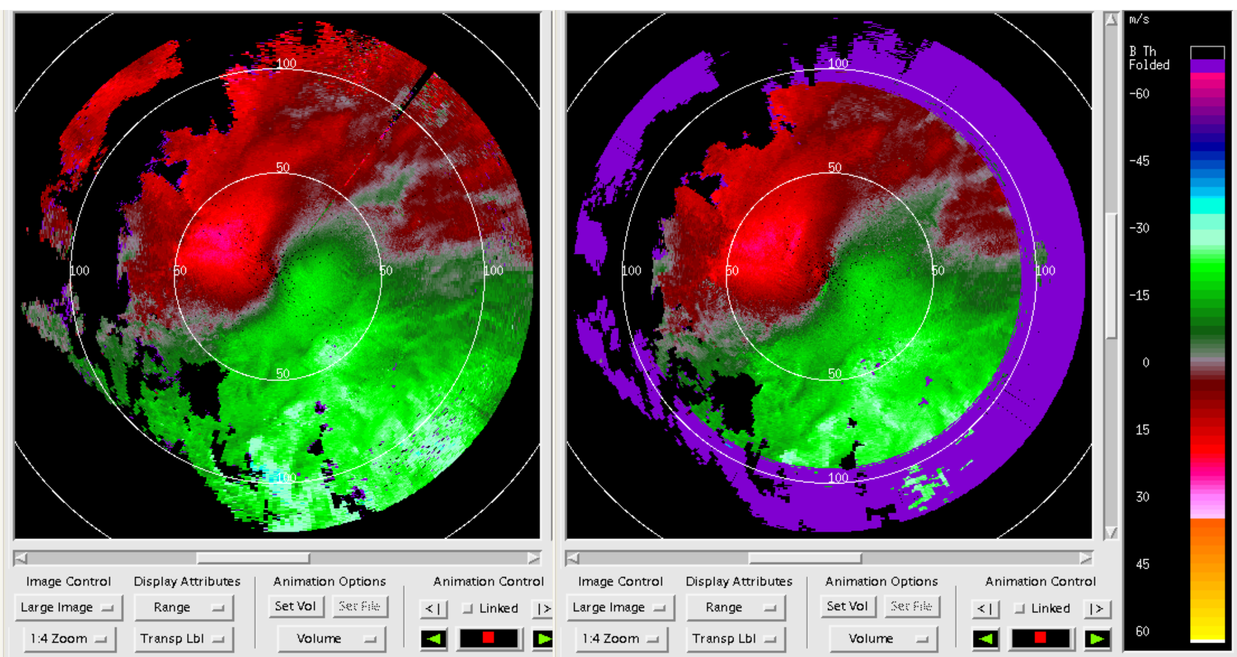

Figure 1b. Side-by-side velocity images for same date and time as in Figure 1a. KCRI on left is running with the enhanced VCP 121 and KTLX on right is running with the baseline VCP 121. Red colors indicate motion away from the radar; green colors indicate motion towards the radar. Note for KTLX nearly all signal beyond 175 km (95 n mi) is range folded. Range rings are same as Figure 1a

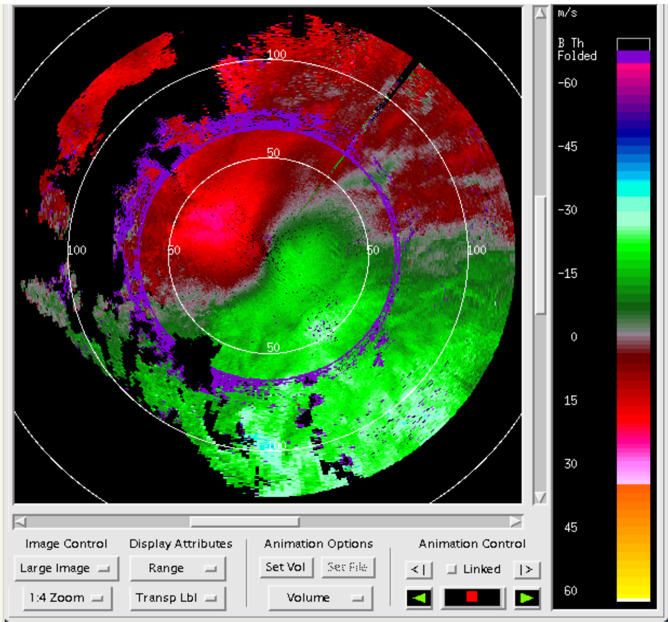

Figure 1c KCRI velocity image for same date and time as in Figure 1b. The 2nd and 3rd Doppler cuts were omitted thus simulating VCP 211. Note the band of range folding between 117 and 137 km. Range rings are same as Figure 1a.

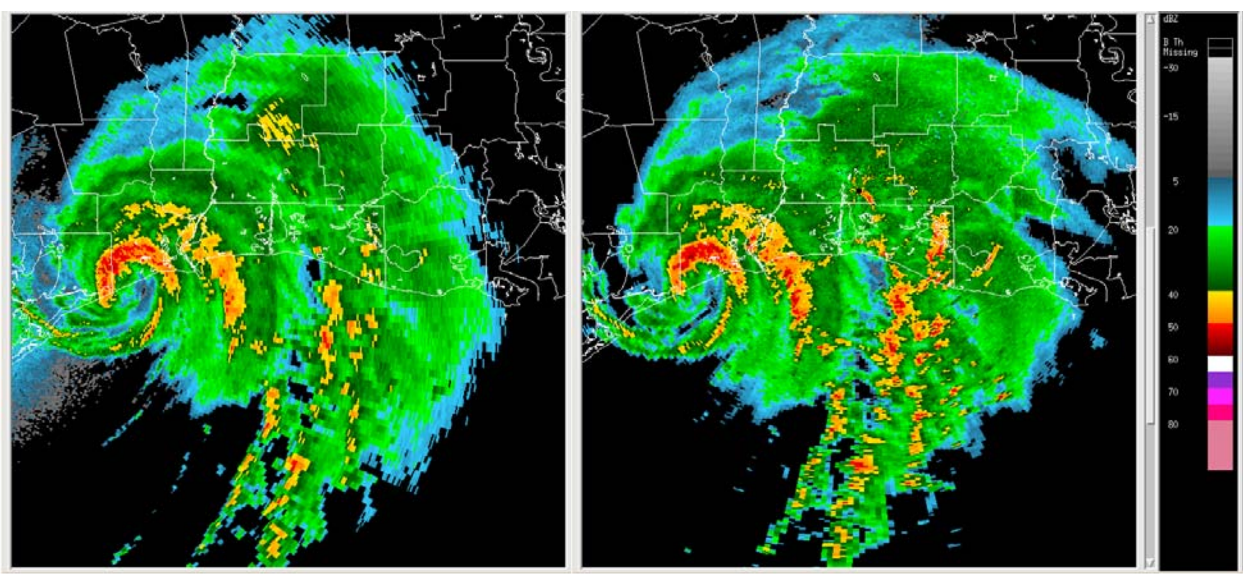

Figure 2a. Side-by-side comparison of reflectivity images from KHGX (left) and KLCH (right) for 07Z on September 13, 2007 about the time of Hurricane Humberto's peak intensity. Coverage and overall intensity are similar around the eye located left center in each image. KLCH is located about 204 km east-northeast of KHGX.

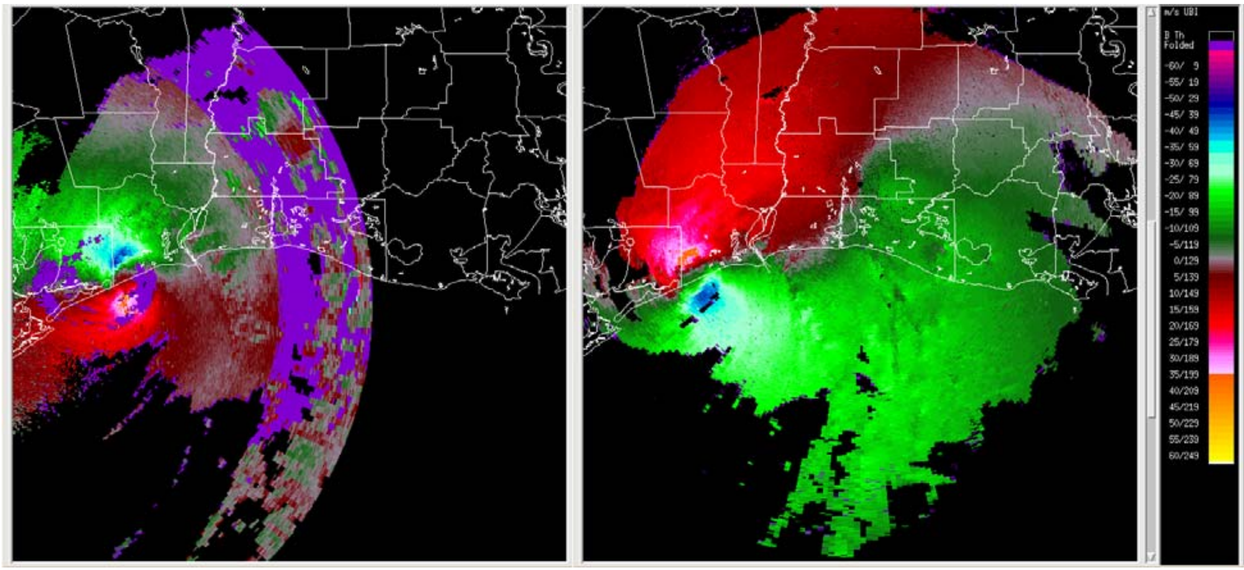

Figure 2b. Side-by-side comparison of velocity images from KHGX (left) and KLCH (right) for 07Z on September 13, 2007 about the time of Hurricane Humberto's peak intensity. KHGX is running the baseline VCP 121 and KLCH is running the enhanced VCP 121. Note the obstruction of the peak winds in the eye (left center in each image) due to range folding for KHGX. KLCH is located about 204 km (110 n mi) east-northeast of KHGX.

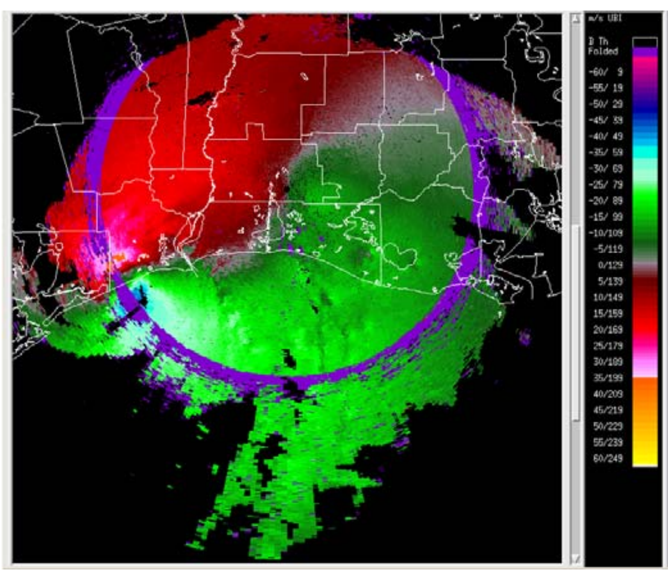

Figure 2c. KLCH Velocity image for same date and time as in Figure 2b. The 2nd and 3rd Doppler cuts were omitted thus simulating SZ-2 alone. Note the band of range folding between 117 km and 137 km that obstructs the peak winds in the eye (left center).