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RADAR RANGE AND VELOCITY AMBIGUITY MITIGATION: CENSORING METHODS FOR THE SZ-1 AND SZ-2 PHASE CODING ALGORITHMS

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1. Introduction

Proper censoring of contaminated or invalid data is essential for the National Weather Service (NWS) Weather Surveillance Radar – 1988 Doppler (WSR-88D) to be practical for forecasters and automated algorithms. The planned upgrade of the WSR-88D network to Open Radar Data Acquisition (ORDA) beginning in January 2005 will change radar processing and base data computation significantly, necessitating the development and fielding of new radar data censoring algorithms.

Doppler radars have fundamental limits on the unambiguous range (r_u) and unambiguous, or Nyquist, velocity (v_N) resulting from the facts that both r_u and v_N are a function of pulse repetition frequency (PRF). The product $r_u x v_N$ is equal to a constant, thus, changing the PRF to increase r_u results in a decreased v_N. At the wavelength of the WSR-88D (~10 cm) a single PRF with acceptable v_N and r_u at low elevation angles does not exist. Currently, the NWS uses a split cut scanning strategy at the lowest two elevation angles, consisting of a long range scan for reflectivity and a shorter range scan for the Doppler measurements separated in time by about 20 s. The reflectivity scan is designed so that overlaid weather echoes are not possible within the troposphere and the Doppler scan is designed to resolve the radial velocity of most weather events, but may contain overlaid echoes. The reflectivity scan is used to sort the location of range overlaid echoes in the Doppler scan and place the echoes in the appropriate location. In the case of overlaid echoes, the signal with the weaker power return cannot be recovered and is censored from the Doppler scan. Further, both overlaid echoes are censored if the powers are within 5 dB of each other. This threshold can be set to 10 dB at the operator's discretion. The relative powers are computed from the long range scan. This method results in large regions of the Doppler scan being censored.

The NWS will be implementing range and velocity ambiguity mitigation techniques that utilize phase coded transmit waveforms on the WSR-88D radar network beginning in 2005. The phase code chosen was designed by Sachidanda and Zrnic (1999, SZ99 hereafter), called the SZ(8/64) code, and has characteristics which optimize the recovery of both the strong and weak overlaid echoes. In this context the strong and weak trips are defined using the powers of the weather echoes and not including the contribution of the ground clutter power. The initial implementation uses a split-cut strategy including a long range scan (without phase coding) for reflectivity and a short range, phase coded scan to obtain the radial velocity and spectrum width measurements at the two lowest elevation angles (referred to as SZ-2). A stand alone technique using a single short range, phase coded scan has been developed for possible implementation at higher elevation angle scans (referred to as SZ-1). The reflectivity scan will again be long enough in range to eliminate the possibility of overlaid echoes. The short PRT, phase coded scan will be designed to allow no more than four overlaid trips.

These powerful new methods allow recovery, rather than censoring, of both the strong and weak overlaid echoes, substantially reducing the amount of censored Doppler velocity data (purple haze). These new phase coding algorithms cannot recover 100% of the overlaid echo and thus require new censoring methods in order to be successfully deployed. This paper will discuss what contaminates the SZ-1 and SZ-2 recovered radial Doppler data, propose censoring methods for SZ-1 and SZ-2, and show results using real data.

2. SZ-1 and SZ-2 censoring requirements

The precision and accuracy requirements for radial velocity data are given in the NEXRAD Technical Requirements (NEXRAD Joint System Program Office, 1986) and are a standard deviation of 1 ms^{-1} and precision of 0.3 ms^{-1} for SNR > 8 dB. For lower SNR values standard deviation values up to 2 ms^{-1} may be acceptable (SZ99). There are several reasons that the SZ-1 and SZ-2 recovered velocities might, be invalid and fail to meet the technical requirements.

The most obvious cause of invalid velocity data occurs if the total received power does not have adequate signal to noise ratio (SNR). In order to make reasonable measurements the signal must be typically 3 to 5 dB above the noise floor of the radar.

Sachidananda and Zrnic (1999) showed that the standard deviation of the recovered weak trip velocity was dependent the ratio of strong trip power (P_1) to weak trip power (P_2) and both strong and weak trip spectrum widths (W_1 and W_2, respectively). If the power ratio is too great, the variance of the velocity estimates becomes unacceptably large. Figures 6(a), 7(a) and 8(a) in SZ99 are reproduced in Figure 1 and show the standard deviation of recovered weak trip radial velocity as a function of power ratio, P_1/P_2, and W_1 for W_2 values of 4 ms^{-1}, 6 ms^{-1} and 8 ms^{-1}, respectively. A large number of simulated spectra were used to produce the plots presented in Figure 1 (SZ99) and are validated by experiments using measured weather spectra by Hubbert et al. (2003), as shown in Figure 2. For the analysis presented in Figure 2, approximately 5000 experimental time series were selected with various powers and spectrum widths. Pairs of time series were than selected, with one being phase coded as first trip and the other as second trip. The phase coded time series were than combined, thus simulating experimental phase coded data. The moments were recovered using SZ-1 processing and compared to the moments computed from the original time series data (non-phase coded). Figure 2 shows the results for W_2 between 3.75 and 4.25 ms^{-1}, and can be compared to Figure 1(a) (note the change in the x axis and color axis limits).

Another source of leakage is the sum of the powers from system noise and the remaining trips' power folded onto the recovered trip. This means that to recover the strongest trip (trip 1), it must have enough power to overcome the sum of the system noise, trip 2, trip 3 and trip 4 powers. Here the trip number refers to the strength of the trip and not its location. To recover trip 2, it must overcome the sum of system noise, trip 1 residue, trip 3 and trip 4 powers. Note that the trip 1 power is notched out during the recovery of trip 2 with SZ-1 and SZ-2 processing, but some residual power may remain.

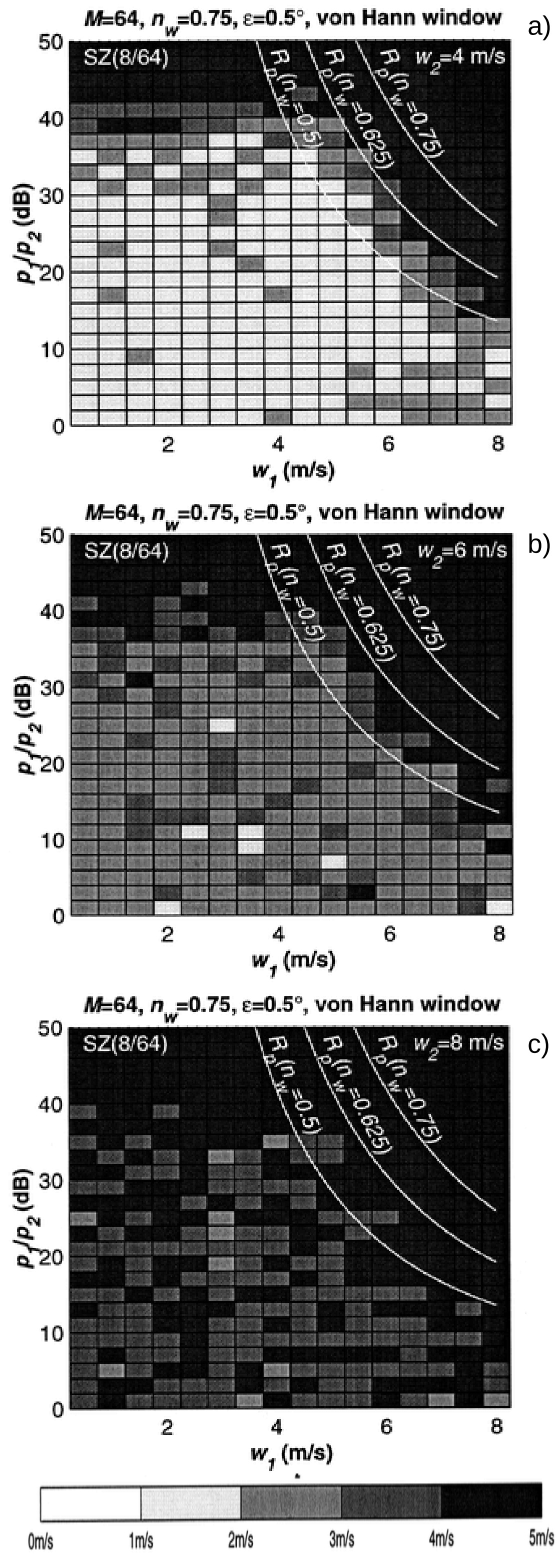

Figure 1. Plots of power ratio (dB) versus strong trip spectrum width (ms-1) for weak trip widths of a) 4 ms^{-1}, b) 6 ms^{-1} and c) 8 ms^{-1}. The data are from simulations (SZ99).

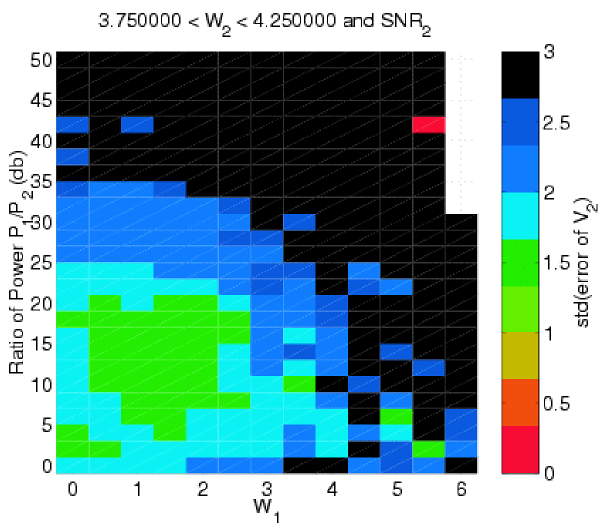

Figure 2 Plot of power ratio (dB) versus strong trip spectrum width (ms^{-1}) for weak trip widths from3.75 to 4.25 ms^{-1}.

Strong ground clutter echoes can leak through clutter filters leaving clutter residue, contaminating the base data estimates. This is a result of the power of the clutter echo being spread throughout the velocity spectrum rather than being limited to velocity values near 0 ms^{-1}. This effect is a result of the spectral response of the window applied to the time series data. Therefore if the clutter to signal ratio (CSR) exceeds a threshold, which is a function of the spectral response of the windowing, the radial velocity estimates are not valid. This contamination cause is not related to the SZ algorithms and exists in the current WSR-88D data. Currently, there is no censoring to deal with clutter leakage, however, with the spectral processing used in the SZ algorithms, CSR can be accurately estimated. The CSR in combination with the known spectral response of the window can be used to develop an appropriate censoring criterion.

The weak trip velocity cannot be recovered if there are ground clutter echoes in the weak trip. If two ground clutter echoes are overlaid neither strong nor weak trips can be recovered.

3. SZ-1 and SZ-2 censoring algorithms

Separate censoring methods are needed for the SZ-1 and SZ-2 algorithms, due to the difference in information available for use. The SZ-2 algorithm has a separate long range scan (with no phase code applied) and a shorter range velocity scan with phase coding. The long range scan is used for the reflectivity estimates and to sort the overlaid echoes from the short range scan and the phase coding allows the strongest and second strongest overlaid trip's velocities to be recovered. The long range scan is also used to compute the values relevant to the validity of the SZ-2 recovered velocity, as described in section 2. These values are used for SZ-2 censoring. The SZ-1 algorithm only contains the short range phase coded scan. The power ratio and out of trip contamination cannot be accurately computed using only the short range scan. This is because the power leaking from one trip to another is unknown and contaminates the power ratio and out of trip contamination estimates. Thus, another censoring strategy must be used in the absence of the information from the long range scan. When the SZ-1 algorithm fails the result is velocity values that are random and noisy. Because weather echoes vary much more smoothly, the noisy characteristics of bad radial velocity estimates can be identified and exploited for censoring. The SZ-1 algorithm operates in the spectral domain and characteristic properties of leakage from another trip are known. Thus the spectrum data can be examined in an objective manner to determine if there is contamination present.

3.1 *SZ-2 censoring*

The current SZ-2 censoring algorithm assumes that the short range scan overlaid trip echoes have been sorted by power. In the proposed volume scan pattern (VCP), there is the possibility of 4 trips containing weather echoes. SZ-2 currently separates the strongest two trips, referred to as the strong trip and weak trip. The third and fourth strongest trips are not recovered.

The SZ-2 recovered Doppler estimates are censored if either the long range, or short range powers do not satisfy the SNR thresholds currently in the WSR-88D VCP definitions. The SNR threshold is applied to both scans to help account for differences in received power between the long and short range scans due to advection and development/decay of weather echoes.

The ratio of the strong trip to weak trip power is computed from the long range scan and used to censor the weak trip by comparison to thresholds based on the studies presented in Figures 1 and 2. The boundaries for the power ratio censoring are straight lines described by 3 parameters: Threshold power, intercept spectrum width and slope. These boundaries are represented in Figure 3, where the gray region is censored and the white region is not censored. As implied by Figure 1, there are different censoring boundaries required for different values of weak trip spectrum width (W_2). The spectrum width values used are normalized by the Nyquist interval ($2*v_n$) to account for the fact that the WSR-88D radars have slightly different wavelengths (to avoid interference) and different pulse repetition times (PRT's) are used in different VCP's. Normalizing the spectrum width censoring values allow the use of one set of values rather than being forced to develop different thresholds for each possible combination of wavelength and PRT. The SZ-2 power ratio censoring parameters are given in table 1.

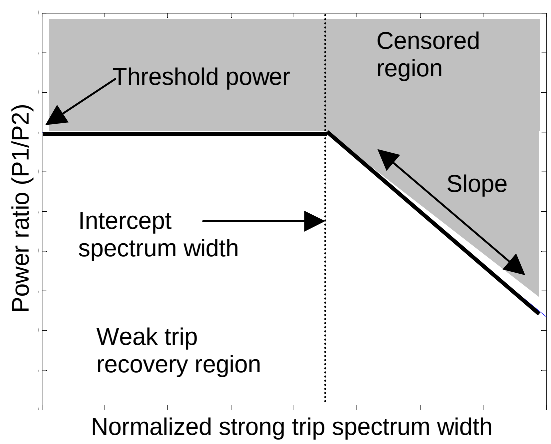

Figure 3. Illustration of the boundaries for censoring based on power ratio.

Table 1

Normalized W_2	Threshold power	Intercept spectrum width	slope
< 0.243	40	0.0699	-20/3
$\geq$ 0.243	35	0.0544	-20/3

The out of trip contaminating power, as described in section 2, can also be computed from the long range scan. The ratio of the recovered trip power (strong or weak) to the sum of the contaminating trip echo is computed. The system, or thermal, noise must also be accounted for. The thresholds for censoring based on out of trip contamination are 0 dB and 5 dB for the strong and weak trip, respectively. In other words, the strong trip must be stronger and the weak trip must be more than 5 dB stronger than the out of trip contaminating echo.

The clutter filter in the upgraded WSR-88D processor that runs the SZ-2 algorithm will operate in the spectral domain, and will allow for computation of the clutter to signal ratio (CSR). The spectral response of the time series window to be used is known and therefore values of acceptable CSR are known. Thus an appropriate CSR censoring threshold can be specified. If the CSR threshold is exceeded than both the strong and weak trip echoes are censored because the clutter leakage will contaminate both trips. The CSR threshold based on the proposed SZ-2 method is 45 dB.

The ground clutter bypass map of the WSR-88D provides the location of normal propagation ground clutter. Thus all trips with ground clutter present in both trips are censored. Also if the ground clutter occurs in the weak trip, the weak trip is censored.

The SZ-2 algorithm computes the weak trip spectrum width from the long range scan, due to biases in the values recovered from the phase coded data. The long range Nyquist interval is limited due to the long PRT used. The normalized spectrum width measured with the long PRT saturates at roughly 0.25 in this case. This is approximately equivalent to 4.5 ms^{-1} in the WSR-88D. Thus, the weak trip spectrum width is censored at normalized values greater than 0.25. This threshold does not effect any other measurements.

3.2 *SZ-1 censoring*

A fuzzy logic algorithm has been developed to identify contaminated radial velocity estimates. The algorithm combines spatial information from the radial velocity field with information derived from the spectrum. The algorithm has been designed to avoid censoring weather phenomena that may appear high in variance to an automated algorithm. The surface divergence of microbursts, the convergence of outflow boundaries, and the rotation of mesocyclones and tornadoes are examples of weather events that might have a high spatial variance.

Several parameters, or feature fields, are computed from the radial velocity data and input into the fuzzy logic algorithm. A small region of data is used to compute the feature fields, which include the radial texture, azimuth texture, radial spin and azimuth spin.

The range texture is computed as,

$$\frac{\sum_{j-1}^{M} \sum_{i=1}^{N} range\_difference_{i,j}^{\;2}}{M * N},$$

where range_difference is the gate to gate difference in range of the radial velocity, i and j are the range and azimuth indices, M and N are the number of gates in the azimuth and range direction respectively. The azimuth texture is the same as the range texture, only computed for gate to gate differences in azimuth.

The range and azimuth spin are adopted from Steiner et al (2002) and are a measure of number of times the slope, or first derivative, in the velocity changes sign in either the range or azimuth direction. To compute range spin, we simply count the number of times within the data region the trend in radial velocity changes from increasing in range to decreasing in range, or decreasing in range to increasing in range. Azimuth spin is computed similarly in the azimuth direction. It is important to set a minimum threshold in the change of radial velocity to be counted as a spin change in order to erroneously avoid counting measurement noise.

The texture and spin feature fields are computed separately in range and azimuth to distinguish between the noise of invalid velocity data and weather signals that may appear noisy. Two dimensional fields would appear noisy for strong gradients, convergence, divergence or rotation. These signatures in radial velocity, however, generally result in high texture and spin in either the range or azimuth direction. However, contaminated velocity data result in high texture and spin in both directions. It is also important to map the radial velocity onto a circle from 0 to 2*v_N before computing texture and spin in order to avoid erroneous censoring when the velocity folds.

The velocity spectra parameter is computed for each range gate. The SZ(8/64) code has the property that the lag 1 spectrum is spread evenly through the Nyquist interval as 8 spectral replicas of the signal, and the lag 2 spectrum is spread into 4 replicas. In order to identify contamination at the spectral level, the Nyquist interval is broken into 8 equal partitions, with one bin centered on the estimated velocity. The peak power in each of the 8 spectral bins is computed and sorted from largest to smallest. The average power of the 3 weakest bins is divided by the power in the strongest bin, which contains the estimated velocity. For relatively clean spectra, this ratio should be close to zero and the larger the ratio gets the more out of trip leakage is present.

The 5 feature fields described above are combined in a fuzzy logic context to determine if the data are to be censored. First, membership functions are designed to map each feature field to a range between 0 and 1, with 1 indicating strongest agreement and 0 no agreement. The output of the membership functions is called the interest field. In our case, an interest of 1 indicates velocity data to be censored and 0 indicates valid data. The s-shaped range spin membership function is plotted in Figure 4. Weather echoes typically have spin values near zero and the likelihood, and thus interest value, of contamination increases as the range spin increases. Notice the membership function is not a boundary threshold but allows for varying degrees of interest between spin values of 0 and 0.15.

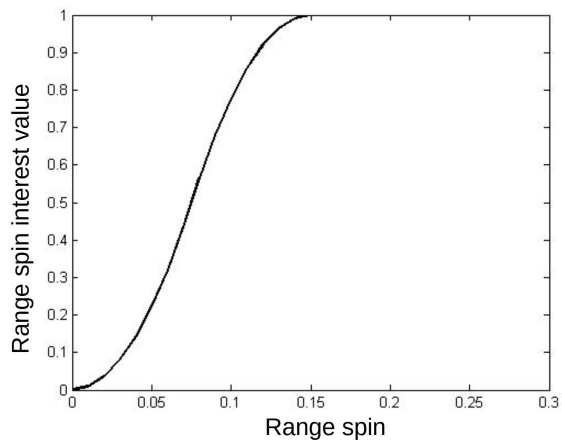

Figure 4. Membership function for range spin.

The membership functions for all 5 feature fields have shapes similar to Figure 4. The values where the membership functions intersect 0 (labeled X0) and 1 (labeled X1) are listed in table 2.

Table 2

	Range spin	Azimuth spin	Range texture	Azimuth texture	Spectral ratio
X0	0	0	40	40	0.15
X1	0.15	0.15	70	70	0.25

The range and azimuth texture interest fields are combined into a single texture interest field using a fuzzy logic “and” operator. This is done because invalid velocity data is noisy in both the range and azimuth directions, while certain weather phenomena appear noisy in either range or azimuth. Experiments were made using 2 different “and” operators, namely the minimum and the product of the two appropriate interest fields. It was found that the minimum operator yielded better separation of valid and invalid velocity values and is used in this study. The two spin interest fields are combined into a single spin interest field in the same way as the texture.

The three interest fields for censoring velocity (texture, spin and spectral ratio) are multiplied by a-priori weights, summed and divided by the sum of the weights to normalize the final weighted sum between 0 and 1. The final de-fuzzification step, and hence the censoring decision, is made by thresholding the weighted sum at 0.5. If the weighted sum is greater than 0.5, the gate is censored.

4. Results

In this section we show examples of results from a single time-series data set containing both long range and short range scans. The time series enables offline processing to obtain results using both the SZ-2 and SZ1 algorithms. This is convenient to compare the censoring results of the two methods. The data was collected using the NCAR S-band dual polarimetric radar (S-Pol) with the Sigmet Corporation RVP8 processor. S-Pol has similar performance characteristics as the WSR-88D radar and the RVP8 is the processor chosen for the Open RDA upgrade.

4.1 *SZ-2 results*

Figure 5 shows a plan position indicator (PPI) of the long range scan power. The power is neither range corrected nor calibrated, but simply spectral magnitude $I^2 + Q^2$. The unambiguous ranges for the first and second trip of the short range scan are denoted by the white solid lines. Strong ground clutter can be seen near the radar, and a large region of second trip echoes with power values that compete with the overlaid first trip echoes in the short range scan. Note that no ground clutter filter was used in the long range scan. The noise floor for SNR computation was determined by averaging the power return from echo free gates.

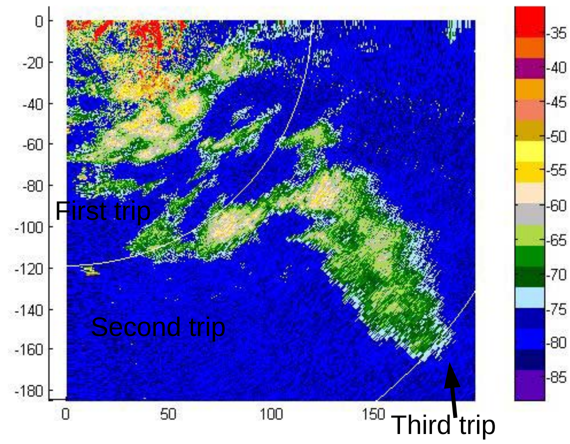

Figure 5. Long range PPI display of power (dB)

The power recovered by the SZ-2 method is presented in Figure 6. Spectral ground clutter filtering was performed on the short range scan. It is instructive to examine the SZ-2 recovered power even though the long range scan is used to compute the power (reflectivity) in the SZ-2 algorithm. The out of trip echo leakage of the strong ground clutter power is easy to see at the beginning of the second and third trips. This contamination is also seen in the SZ-2 recovered radial velocity data as random estimates, shown in Figure 7. The white regions in Figures 7 and 8 are not recovered because they are either the third or the fourth strongest trips. Recall that the SZ-2 algorithm only computes moments for two trips, the strongest and second strongest (referred to as strong and weak respectively).

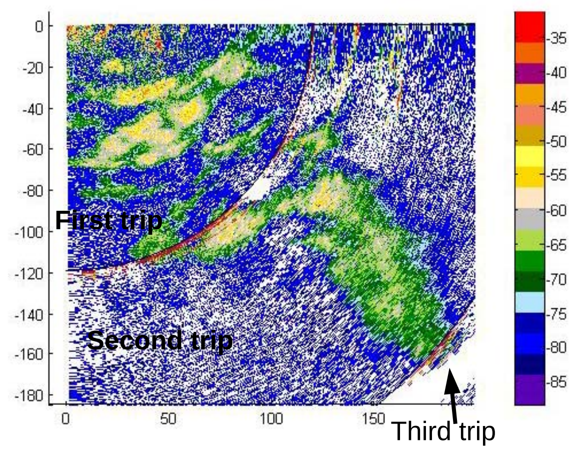

Figure 6. Short range phase coded PPI of SZ-2 recovered power (dB).

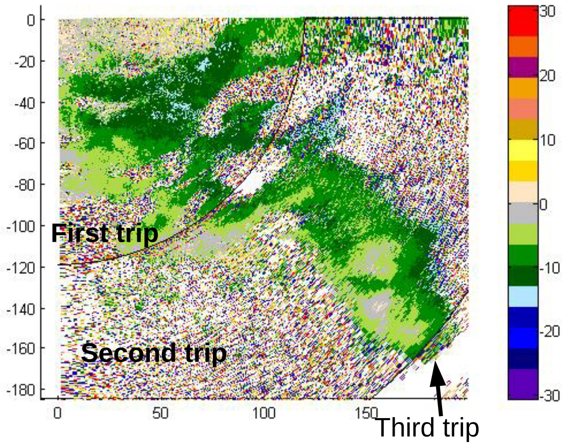

Figure 7. Short range phase coded PPI of SZ-2 recovered radial velocity (ms^{-1}).

Figure 8 is similar to Figure 7 except that the SZ-2 censoring algorithm, as described in section 3.1, has been applied to the data. In Figure 8, data that does not pass the SNR threshold on either the short or long range scans are not displayed (white), and the data in locations that had sufficient SNR, but were censored are displayed as purple. It can be seen that all of the contaminated data are successfully censored, while very little valid velocity estimates are removed. Also, the third trip data are recovered if they are either the strong or weak trip.

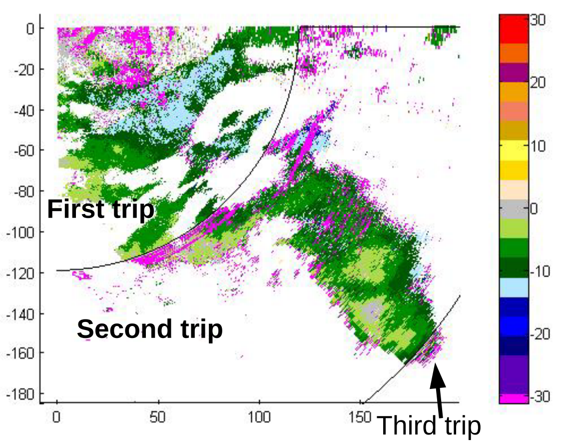

Figure 8. Short range phase coded PPI of SZ-2 recovered radial velocity (ms^{-1}) after censoring.

4.2 *SZ-1 results*

Figure 9 shows the SZ-1 recovered data for the same time series scan as presented in section 4.1. The SZ-1 algorithm recovers the strong and weak trip echoes only within the first two trips.

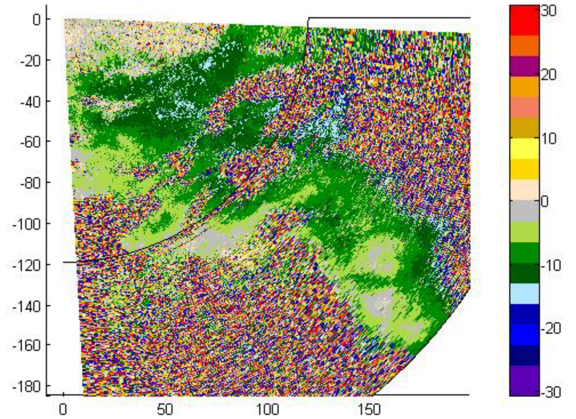

Figure 9. Short range phase coded PPI of SZ-1 recovered radial velocity (ms^{-1}).

The results of applying the SZ-1 censoring algorithm to the data in Figure 9 are presented in Figure 10. The regions without significant SNR in the short range scan are plotted as white and the data with sufficient SNR, but were censored are indicated by purple. Notice that some regions of out of trip leakage that were censored based on the long range scan SNR (plotted as white) by the SZ-2, algorithm (Figure 8) remain in the SZ-1 algorithm and are censored (purple). This difference is because the long range scan is not available for SZ-1 and the short range scan has significant SNR in these regions due to out of trip leakage. It can be seen that the contaminated velocity data are successfully censored using the SZ-1 fuzzy logic censoring algorithm. It can also be seen that in areas of overlaid weather echoes the SZ-1 censoring method removes slightly more data surrounding the contaminated data, compared to the SZ-2 censoring. This small expansion of the censored region is not surprising given the 2-D nature of the feature fields described in section 3.2.

It is possible to apply the current WSR-88D short-range scan censoring method to the data above. The results are presented in Figure 11, and can be compared to Figure 8 (SZ-2) and Figure 10 (SZ-1). Clearly both the SZ-2 and SZ-1 result in a significant improvement in velocity recovery area.

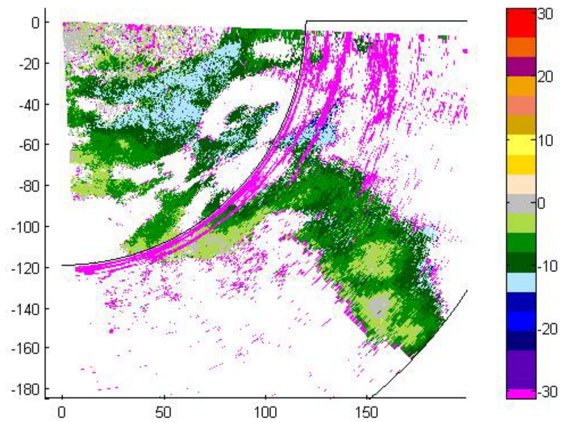

Figure 10. Short range phase coded PPI of SZ-1 recovered radial velocity (ms^{-1}) after censoring.

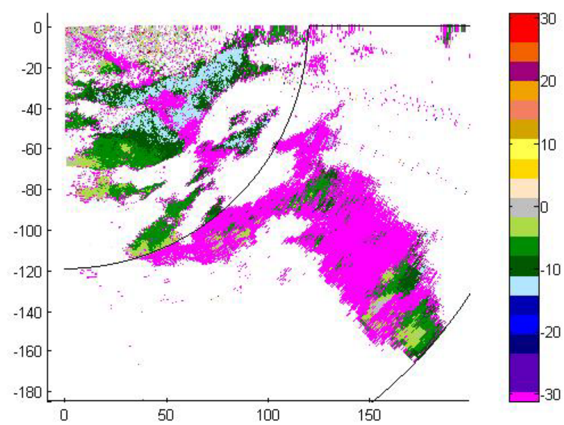

Figure 11. Short range PPI of radial velocity after the current WSR-88D censoring algorithm is applied with a 5 dB threshold (default setting).

5. Acknowledgements

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6. References

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