12.4 DATA QUALITY CONTROL FOR THE SZ(8/64) PHASE CODE FOR THE MITIGATION OF RANGE AND VELOCITY AMBIGUITIES IN THE WSR-88D

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1. INTRODUCTION

The data quality of weather radars such as the NEXRAD WSR-88D is limited by range and velocity folding of echoes. Increasing the PRT (pulse repetition time) will extend the unambiguous range but decrease the unambiguous velocity. Shortening the PRT has the opposite effect. Phase coding the transmitted radar pulses allows separation of multiple trips with appropriate decoding of the received signal. This strategy allows the recovery, rather than censoring, of overlaid echoes and will greatly increase the area coverage compared to the current WSR-88D processing.

The SZ(8/64) code (Sachidananda and Zrnic 1999) allows the resolution of signals from as many as four trips in a wide variety of conditions. The SZ algorithm, using spectrum reconstruction techniques, has been developed and tested for suppressing the out of trip contamination to recover the spectral moments from the two strongest trips.

An important aspect of the SZ algorithm is censoring the recovered moment data when there is contamination from competing trips. Two censoring algorithms are outlined in this paper: one for use when long PRT data is available and one for when there is not.

Filtering ground clutter without adding unacceptable biases in the recovered spectral moments is important to radar data quality. Currently in the WSR-88D, ground clutter power is removed via the use of IIR (infinite impulse response) filters which effectively remove the power around zero velocity but which also impart a phase delay which is non-linear. This phase delay will degrade the performance of the SZ algorithm causing unacceptable biases in the weak trip velocity.

2. SZ ALGORITHM

The theory of SZ(8/64) phase coding is described in Sachidananda and Zrnic (1999). When the first trip (considered the strong trip here) echoes are made coherent, the second trip is modulated by the SZ(8/64) modulation code (the time-series considered here are 64 samples in length). The spectrum of the phase modulated second trip consists of eight, equally spaced, replicas of the spectrum of the "true" non-phase coded second trip echo. To recover the moments of the weak trip signal, at least two of these replicas need to be preserved. Thus 3/4 of the weak trip spectrum can be "notched" or zeroed. The 3/4 notch is typically centered at the mean velocity of the coherent first trip, but the placement can vary depending on the existence of ground clutter. An attractive feature of the SZ(8/64) phase code is that the autocovariance function of the phase code sequence is 1 for lags 0, 7, 15 etc., and zero otherwise. Thus velocity estimates of the first trip coherent signal are unbiased by the overlaid modulated second trip echo.

The signal processing steps in executing the SZ(8/64) algorithm is as follows (moments with "^" are recovered while others without are "truth" calculated from the original time series). The I&Q time-series is cohered to the strong trip and then the power ($\hat{P}_1$), mean velocity ($\hat{V}_1$), and spectrum width ($\hat{W}_1$) are estimated using the pulse-pair technique. A notch filter (typically 3/4 Nyquist interval) is applied to remove the strong signal in the spectral domain. The notch is centered at the first moment estimate of the current (stronger) trip echo. The power of the weaker signal ($\hat{P}_2$) is now estimated by computing the signal power of the notched spectrum and applying the proper gain to compensate for the notch. The signal is then cohered to the weaker trip and the mean velocity ($\hat{V}_2$) is estimated for this trip. The truncated spectral coefficients, from the notch, create symmetric sidebands in the re-cohered signal that affect the estimate of the spectrum width ($\hat{W}_2$). To mitigate this, the weaker signal is reconstructed using "magnitude deconvolution" and then the pulse-pair spectrum width estimate is computed.

In the newly proposed volume coverage patterns (VCP) for the WSR-88D, each of the two lowest elevations consist of two scans: a long PRT, non-phase coded scan followed by a short PRT SZ(8/64) phase-coded scan. This is necessary because of the possibility of as many as four overlaid echoes at these elevations. The SZ algorithm works by processing the trips in order

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of strongest to weakest signal power, thus the trips need to be sorted. This is difficult without the long PRT scan when there are more than two competing trips. In the next two higher evaluation scans, if the SZ algorithm is used, there are only two possible trips and thus the long PRT scan is not needed. The processing that includes the long PRT data is referred to as SZ-2 and the processing that does not is called SZ-1.

3. DATA

Sachidananda and Zrnic (1999) evaluated the use of SZ(8/64) with the SZ moment recovery algorithm. Their technique used numerically simulated I&Q data. Frush et al. (2002) demonstrated the technique using experimental data from NCAR's S-band polarimetric radar, S-Pol, comparing the recovered moments to the moments from the long PRT data. The SZ algorithm was further statistically evaluated with experimental data in Hubbert et al. (2003). In this case, experimental, non-phase coded I&Q data was phase coded using SZ(8/64) off-line and overlaid to simulate I&Q data containing multiple trip echoes transmitted using the SZ(8/64) phase code. This is referred to as concatenated data and will be used in the next section. Until recently, testing of SZ algorithm has been limited to off-line processing of either simulated or experimentally recorded I&Q time series data. In May of 2003, NCAR installed SIGMET's RVP8 receiver processor in parallel with the existing processor on S-Pol. This provides the capability to evaluate the SZ algorithm real-time as well as to record the raw I&Q time-series onto a terabyte RAID (Redundant Array of Inexpensive Disks) for further off-line testing. In this paper, we use the last three types of data.

4. CENSORING

While the data coverage using the SZ methods, described above, will be dramatically increased, robust censoring of contaminated data is essential to the success of the algorithms. There are several reasons the SZ recovered moments can be contaminated, thus requiring the data to be censored. First, the power of the desired trip must overcome the system noise and the sum of the competing trip echoes. Second, if the power ratio of $\hat{P}_1$ to $\hat{P}_2$ exceeds a threshold, the leakage of $\hat{P}_1$ into trip 2 will prevent the recovery of trip 2 moments. This threshold is dependent on the spectrum widths of both trip 1 and trip 2 (Sachidananda and Zrnic 1999).

The two different applications of the SZ algorithm currently being considered for the WSR-88D system require two different censoring algorithms. For SZ-2, the long PRT data is available to sort the short PRT power into the proper trip. This information can be used to censor the phase coded, short PRT data using the known performance of the algorithm. The performance of the SZ(8/64) algorithm has been computed theoretically (Sachidananda and Zrnic 1999) and verified with real data (Hubbert et al. 2003). For the SZ-1 technique there is no long PRT data available, so another method is required. SZ-1 censoring takes advantage of the fact that the recovered velocity estimates in contaminated regions are random. Therefore a fuzzy logic algorithm has been developed to separate the coherent velocity estimates of weather data from the speckled velocity estimates of contaminated regions. These two censoring algorithms are outlined in this section.

4.1 SPECTRAL CENSORING

For both SZ-1 and SZ-2 a check is performed during the weak trip processing to test for the existence of excessive clutter. After deconvolution is performed, most of the weak trip power should be coherent, i.e. there should not be either significant sidebands or spectral replicas. The test is performed by breaking the deconvolved weak trip spectrum into 8 equal-sized segments. The peak spectral value for each of the segments is found. If more than four of the peaks are within 6 dB of the maximum peak value, then the SZ algorithm, weak trip estimates are censored. Figure 1 and Figure 2 show examples of a weak trip spectrum after deconvolution. Figure 1 shows the case where there is not significant contamination, and therefore the data was not censored. Figure 2 shows the opposite.

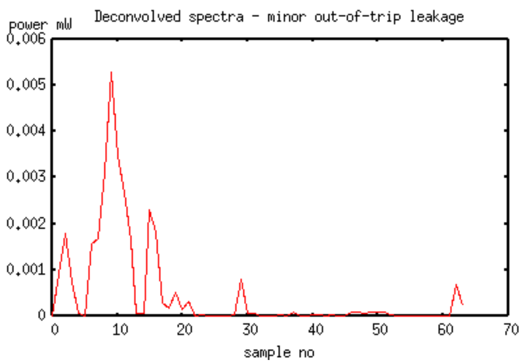

Figure 1: Example of weak trip spectrum after deconvolution without significant leakage.

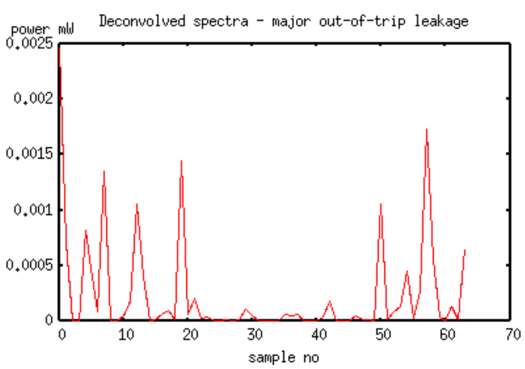

Figure 2: Example of weak trip spectrum after deconvolution with significant leakage.

Figure 3 and Figure 4 show data recorded using SIGMET's RVP8 on NCAR's S-Pol radar. Each range ring corresponds to 50 km, and the unambiguous range for the short PRT is 150 km. Figure 3 shows the velocity field of a long PRT scan. Notice the existence of significant velocity folding. In Figure 4, the recovered velocity field from the SZ(8/64) phase coded, short PRT scan is displayed. The gates where there is no data have been censored, either because of low signal to noise ratio or because of strong trip leakage into the weak trip. In particular, there is a ring of censored data near 150 km from the radar, just beyond the unambiguous range. The power from the clutter immediately around the radar is leaking into the weaker, second trip, and is being censored by the spectral leakage test. An important point to note is that this data shows the results from an intermediate censorship step.

4.2 SZ-2 CENSORING

The SZ-2 censoring algorithm has two steps. The first step censors the recovered moments based on the signal to noise ratio (SNR) in each trip. The second step thresholds on the power ratio of the strongest trip (trip 1) to the second

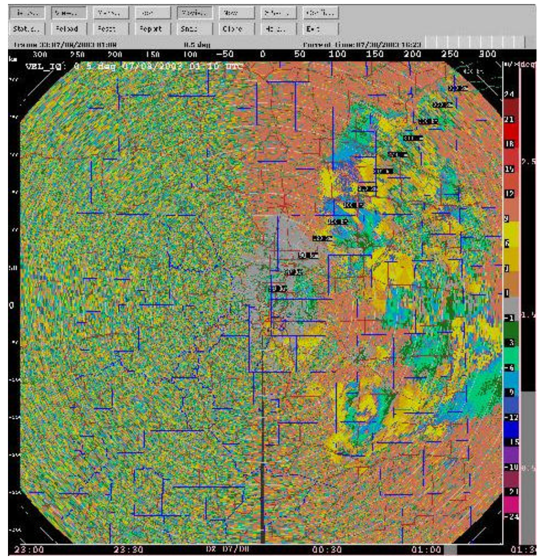

Figure 3: Long PRT velocity from S-Pol using RVP8.

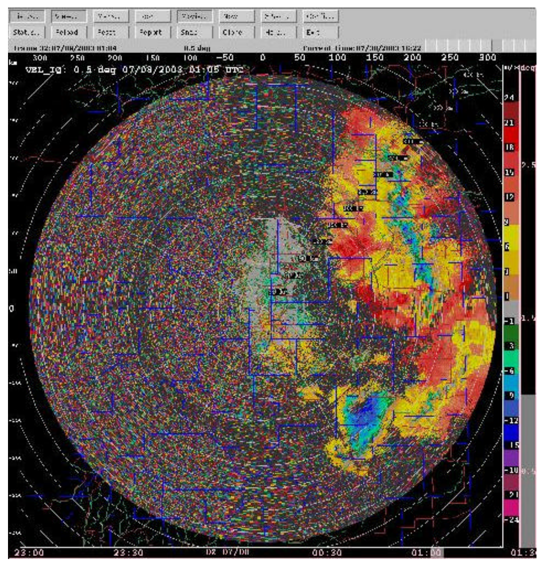

Figure 4: SZ(8/64) phase coded, short PRT velocity from S-Pol using RVP8. The missing data points are a result of the strong trip leakage test. Note that this data show the results from an intermediate censoring step and is NOT the final product.

strongest trip (trip 2). The power ratio thresholding is only necessary for the trip 2 moments. In steps 1 and 2 it is assumed that the power from each trip has been sorted and that the power ratio has been computed using the long PRT data.

4.2.a. Step 1

The possible out of trip contamination or noise power is computed from the long PRT scan and compared to the power from the trip being recovered. For recovering the strong trip, the strong trip power (P_1) must overcome the sum of powers from system noise and the competing trip echoes, i.e. trips 2, 3 and 4. Recovering the trip 2 moments requires the trip 2 power (P_2) to overcome the sum of the system noise and competing trip power, i.e. trips 3 and 4 (recall that trip 1 is removed by the 3/4 Nyquist interval notch). For both trip 1 and trip 2 recoveries it has been found that the signal should exceed the contaminating noise power by 3 dB for reliable moment recovery. Thus if the power of the desired trip (estimated from the long PRT scan) is below the noise power in dB plus 3 dB, the data is censored.

4.2.b. Step 2

Censoring boundaries based on power ratio (P_1 / P_2) and spectrum width have been defined following Sachidananda and Zrnic (1999) and Hubbert et al. (2003). Accordingly, multiple censoring boundaries have been designed for different weak trip spectrum widths (W_2). The ranges of separate boundaries are W_2 < 5 ms^{-1}, 5 ms^{-1} $\leq$ W_2 < 7 ms^{-1} and $W_2 \geq$ 7 ms^{-1}. The boundaries for the first two ranges of W_2 are piece-wise continuous line segments. Figure 5 shows the censoring boundary for W_2 < 5 ms^{-1} plotted with W_1 on the abscissa and power ratio on the mantissa. Data lying above the boundary are censored, denoted by the gray region in Figure 5. Figure 6 shows the censoring boundary for 5 ms^{-1} $\leq$ W_2 < 7 ms^{-1} (solid black line). Again data lying above the solid line are censored, denoted by the gray region in Figure 6, and for reference the boundary for W_2 < 5 ms^{-1} (Figure 5) is re-plotted (dashed thin line). Finally, if W_2 $\geq$ 7 ms^{-1} the data are censored.

The equation for the censoring boundary is:

Case: W_1 < intercept

power ratio > threshold

Case: W_1 $\geq$ intercept

power ratio>slope*(W_1 - intercept) + threshold

where threshold refers to the height of the horizontal line segment, intercept is the point at which the two line segments meet and slope is the slope of the tilted line segment.

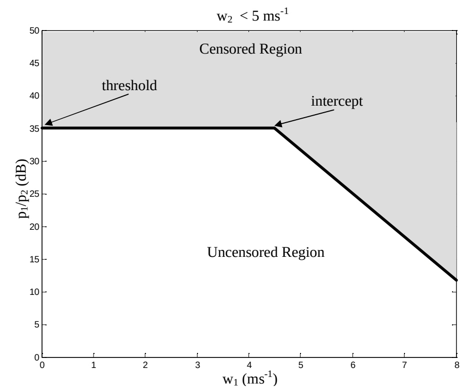

Figure 5: The power ratio censoring boundary for w_2 < 5 ms^{-1} is plotted as a function of the strong trip spectrum width (w_1). The gray color denotes the censored region.

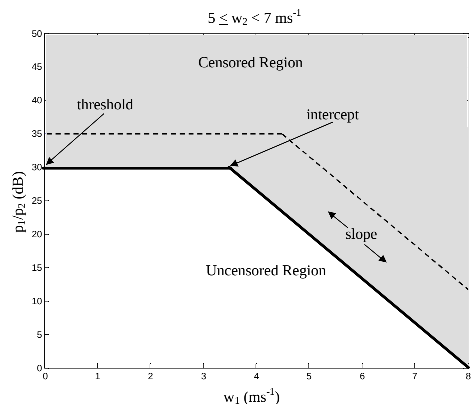

Figure 6: The censoring boundary for 5 ms^{-1} < w_2 < 7 ms^{-1} is plotted as the solid black line. The thin dashed line is the boundary for w_2 < 5 ms^{-1} from Figure 5.

The parameters for the two ranges of W_2 are listed in table 1.

Table 1

Range of W_2	W_2 < 5 ms^{-1}	5 $\leq$ W_2 < 7 ms^{-1}
Threshold	35 dB	30 dB
Intercept	4.5 ms^{-1}	3.5 ms^{-1}
Slope	-20/3	-20/3

Figure 7, Figure 8, and Figure 9 show data recorded from KOUN, the NEXRAD testbed located at NSSL in Norman, OK. Figure 7 shows the power from the long PRT scan. In Figure 8, the uncensored velocity field from the SZ(8/64)

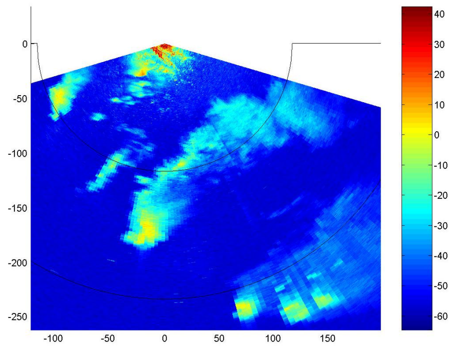

Figure 7: Long PRT Power recorded on KOUN (WSR-88D)

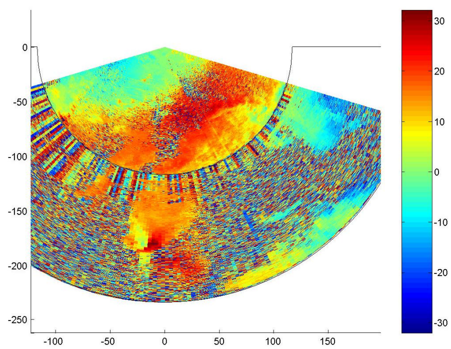

Figure 8: Short PRT Velocity recorded on KOUN (WSR-88D).

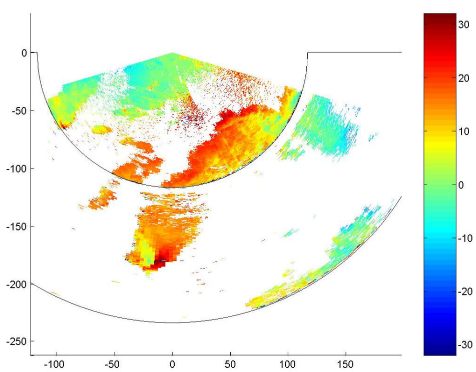

Figure 9: Short PRT velocity, recorded on KOUN (WSR-88D), after Censoring

phase coded, short PRT scan. Figure 9 shows the results from the SZ-2 censoring algorithm. The performance of the algorithm looks quite good.

Note that the striping in Figure 8 just past the first unambiguous range is due to significant leakage from the strong clutter near the radar and due to imprecise knowledge of the actual transmitted phase codes. This does not occur when the actual transmitted phase codes are used for the processing, rather than the theoretical phase codes.

4.3 SZ-1 CENSORING

In the absence of the long PRT scan data, the contaminating out of trip signal and power ratio are unknown. Although the powers, $\hat{P}_1$ and $\hat{P}_2$ are estimated by the SZ(8/64) algorithm, the estimated power ratio is biased by any leakage of signal and therefore is not a reliable tool for censoring. However the velocity estimates in contaminated regions are random in nature and a fuzzy logic algorithm has been developed to identify and censor these regions. It is important not to censor weather echoes that may appear to be noisy to an automated algorithm, such as tornados, meso-cyclones, microbursts, convergence lines and strong gradients. These natural sources of radial velocity variance in weather data generally have high variance in either the radial direction or the azimuthal direction whereas the noisy data, that needs to be censored, are noisy in all directions. This is taken into account in the fuzzy logic censoring algorithm.

The inputs to the fuzzy logic algorithm are so called feature fields, computed from the radial velocity estimates. These feature fields are designed to indicate how noisy the estimates are. These fields include the texture, range spin, and azimuth spin of the velocity. A small patch of data surrounding the range gate in question is used for computing the feature fields. The texture is a measure of the gate-to-gate variability and is the sum of the squared differences in the radial velocity from one range bin to the next divided by the number of gates in the patch. Contaminated data has large velocity texture values while weather echoes have relatively small values. The range spin is the total number of inflections in range on a gate-to-gate basis that exceed an *a priori* threshold. In other words the number of times the trend in range of the data changes. The threshold prevents measurement noise from erroneously indicating inflection points. The azimuth spin is similar to the range spin except that it is computed in the azimuthal direction. Noisy contaminated data will have many inflection points while weather targets have few.

Fuzzy logic membership functions have been designed to indicate contaminated data for each of the feature fields. There are two output classes possible for the fuzzy logic algorithm: censored data and good data. Each membership function contains values between 0 and 1,

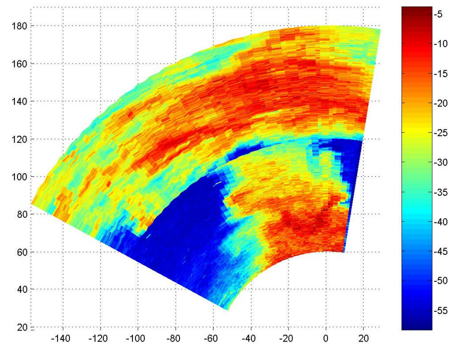

Figure 10: Concatenated Power from non-phase coded short PRT scan.

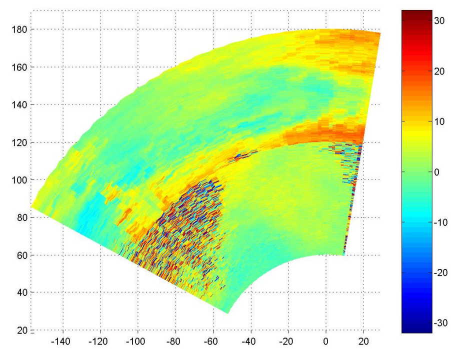

Figure 11: Concatenated SZ recovered Power from non-phase coded short PRT scan

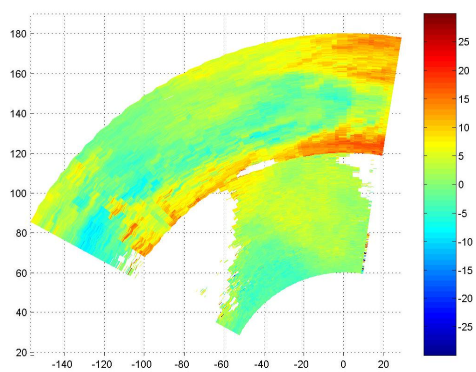

Figure 12: Concatenated SZ recovered Power from non-phase coded short PRT scan after SZ-1 censoring.

indicating the degree to which the feature field indicates the output class “censored data”, with 1 being the highest indication and 0 meaning no indication.

The interest values are computed by applying the appropriate membership function to the feature fields resulting in interest values between 0 and 1. The interest values for range spin and azimuth spin are combined using a fuzzy logic “or” operator. This is done to account for the fact that censored data should be noisy in both the range and azimuth directions and is accomplished by using the minimum of the two interest values. The results are then multiplied by the texture interest values resulting in combined interest values ranging between 0 and 1. The final step (de-fuzzification) is to apply an appropriate threshold, in this case 0.5, i.e. if the combined interest field value is above 0.5, the data are censored.

Figure 10, Figure 11, and Figure 12 show data from 2 separate scans concatenated in range. In Figure 10, the power from the 2 non-phase-coded, short PRT scans, are simply concatenated. In Figure 11, the same 2 scans are phase-coded for trip1 and trip 2, and then added together (I&Q). This data is then processed using SZ-1. The recovered velocities for trip 1 and 2 are then concatenated. Figure 12 shows the results from processing the data in Figure 11 through the SZ-1 censoring algorithm. Again, the performance seems quite good.

5. IIR CLUTTER FILTERING

On the current WSR-88D system, ground clutter power is removed via the use of IIR (infinite impulse response) filters which effectively remove the power around zero velocity but which also impart a phase delay which is non-linear. This phase delay will degrade the performance of the SZ algorithm causing unacceptable biases in $\hat{V}_2$. To show this, a 3/4 notch is applied to the spectrum of the modulation code. The corresponding time-series is calculated using a discrete inverse Fourier transform. This time-series is re-cohered and the magnitude of the spectrum is calculated. This same process is again carried out except the original modulation code time series is first passed through an IIR clutter filter. The resulting spectra are shown in Figure 13 The solid lines are the resultant spectrum without clutter filtering and the dashed lines are with clutter filtering. As shown by Sachidananda and Zrnic (1999), the spectrum of the recovered weaker trip has a primary spectrum replica with 3 accompanying replicas on each side. These correspond to the 7 solid line spikes in Figure 13. Since the 6 side replicas are symmetric about the primary replica, $\hat{V}_2$ is unbiased. The spectrum of the clutter filtered version of the modulation code does not possess such symmetry around the zero velocity and therefore $\hat{V}_2$ will be biased. Simulation studies performed (not shown) support these results.

Thus, IIR clutter filtering and SZ phase coding are incompatible. Therefore, to effectively remove ground clutter and not adversely affect SZ recovered moments, FIR (finite impulse response) or spectral filters should be used. These filters are suitable because they have a constant phase response. Currently we are investigating adaptive spectral clutter filters.

6. ACKNOWLEDGMENT

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7. REFERENCES

Frush, C., R.J. Doviak, M. Sachidananda and D.S. Zrnic, 2002: Application of the SZ Phase Code to Mitigate Range-Velocity Ambiguities in Weather Radars, JTECH, 19, 413-430.

Hubbert, J. C., G. Meymaris, and R. J. Keeler, 2003: Range-Velocity Mitigation via SZ Phase Coding with Experimental S-band Radar Data, *Preprints*, 31st Int'l Conf. on Radar, AMS, Seattle, WA.

Sachidananda, M. and D.S. Zrnic, 1999: Systematic Phase Codes for Resolving Range overlaid Signals in a Doppler Weather Radar JTECH, 16, 1351-1363.

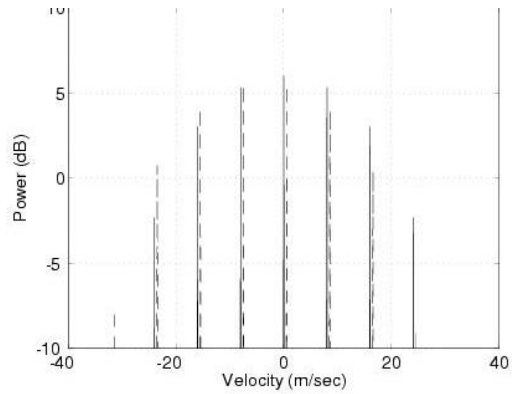

Figure 13: Modulation code of weak trip spectrum. The solid lines show the spectrum without IIR clutter filtering, while the dotted lines show the spectrum with IIR clutter filtering. Note that without clutter filtering, the spectrum is symmetric around 0 m/sec, whereas with clutter filtering it is not.