# Range and velocity ambiguity mitigation on the US NEXRAD network: performance and improvements of the SZ-2 phase coding algorithm

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## 1. Introduction

It is well known that for Doppler radars transmitting uniformly spaced pulses there is a coupling between the maximum unambiguous range and velocity. That is, one can only be increased at the expense of a proportional decrease of the other. Because this fundamental limitation hinders observation of severe weather phenomena, the Radar Operations Center of the US National Weather Service has sponsored the National Severe Storms Laboratory (NSSL) and the National Center for Atmospheric Research (NCAR) to develop methods for mitigating the effects of velocity and range ambiguities on the NEXRAD network. In a joint effort, NSSL and NCAR have recently recommended an algorithm for the initial deployment of range and velocity ambiguity mitigation techniques on the radars' new signal processors. The algorithm, referred to as SZ-2, is based on systematic phase coding that uses the SZ(8/64) code and operates at the lowest elevation angles of the antenna beam.

This paper shows the performance of the SZ-2 algorithm, discusses a few surprises that surfaced after its operational implementation, and describes proposed improvements.

## 2. The SZ-2 Algorithm

Sachidananda and Zrnić (1999) proposed the SZ phase code as a better alternative to random codes (e.g., Laird 1981). SZ phase coding is similar to random phase coding except that the transmitted pulses are phase-modulated with a systematic code consisting of *M* phases that repeat periodically. These codes exhibit properties that make them attractive for the separation of overlaid signals in the spectral domain. That is, if the received signal is cohered for a given trip, the spectra of all out-of-trip echoes consist of evenly spaced replicas of their corresponding coherent spectra. Hence, out-of-trip echoes do not bias the mean Doppler velocity estimate of the coherent signal. Once the velocity is recovered for the strong-trip, the coherent signal is notched out such that the two least contaminated replicas of the out-of-trip (i.e., the weak trip) echo remain. These two replicas are sufficient to reconstruct (or "recohere") the weak-trip echo and recover its mean Doppler velocity. From the family of SZ(*n*/*M*) codes, the SZ(8/64) code was selected for NEXRAD as it gives the best performance in terms of recovery of overlaid signals that are separated by one trip (Sachidananda et al. 1998).

Recovery of strong and weak trip signals can proceed in a stand-alone manner (referred to as the SZ-1 algorithm) or with the aid of an extra scan at the same elevation angle using a long pulse repetition time (PRT) (referred to as the SZ-2 algorithm). Although the latter results in longer acquisition times due to the extra scan, long-PRT data provides non-overlaid power information that is essential in the determination of the location and strength of overlaid trips for the short-PRT scan. Having the long-PRT information available makes the SZ-2 algorithm computationally simpler and more effective than its stand-alone counterpart. Whereas the long-PRT data provides the reflectivity free of range ambiguities, the short-PRT data is used to compute Doppler velocities associated with the two strongest overlaid signals.

The SZ-2 algorithm, which is currently implemented on the US network of weather surveillance radars since the Spring of 2007 (Saffle et al. 2007), incorporates a set of censoring rules to maintain data quality under situations that preclude the recovery of one or more overlaid echoes (Saxion et al. 2007, Ellis et al. 2005). Base data displays characterize this failure by encoding those range locations with overlaid powers using a purple color, normally referred to as the "purple haze".

## 3. Performance of the SZ-2 Algorithm

Fig. 1 shows an example of the reduction in range folded Doppler velocity data using the SZ-2 algorithm in VCP 212 (right) in comparison with the legacy VCP 12 (left). The VCP 212 data at the 0.5 deg elevation was collected by the KCRI radar (a test WSR-88D) in Norman, Oklahoma. The VCP 12 data at the 0.5 deg elevation was collected at nearly the same time on the KTLX radar at Twin Lakes, Oklahoma. A clear tornado signature is visible in the VCP 212 data whereas it is unfortunately obscured by purple haze on the VCP 12 data.

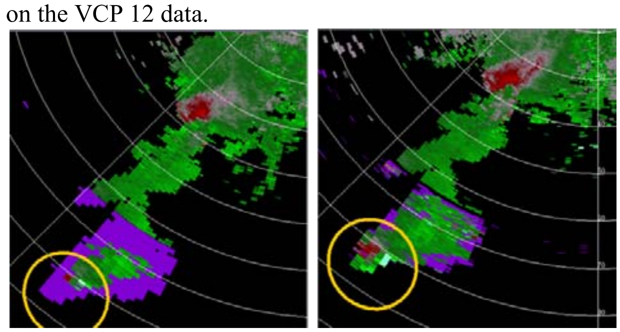

*Fig. 1. Doppler velocity fields for 0.5 deg elevation collected on April 25, 2006 at about 01:33 UTC during a tornado event in central Oklahoma. The image on the left comes from the operational KTLX (legacy) and the one on the right from the test KCRI (SZ-2).*

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Fig. 2 illustrates the first operational selection of a scanning strategy based on the SZ-2 algorithm. The event corresponds to a mesoscale convective system (MCS) observed by the KTLX radar from Twin Lakes, OK on March 30, 2007 at about 19:40 UTC. The two Doppler velocity fields shown in this figure correspond to the times before and after switching from VCP 12 (legacy) to VCP 212 (SZ-2). As expected, Doppler velocity displays obtained with legacy-type processing are significantly obscured by the purple haze which indicates the presence of unresolvable overlaid echoes. On the other hand, the SZ-2 algorithm successfully recovers velocities of the two strongest overlaid echoes.

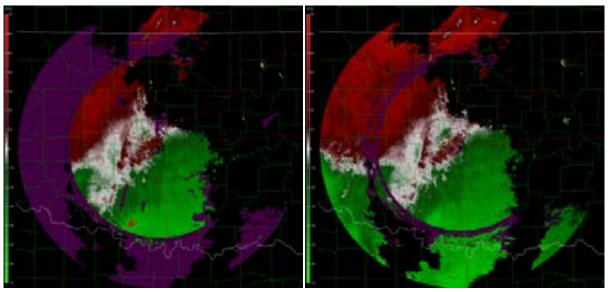


*Fig 2. KTLX Doppler velocity fields for 0.5 deg elevation collected operationally on March 30, 2007 at 19:37 and 19:42 UTC during a severe storm event in central Oklahoma. The image on the left corresponds to a legacy VCP and the one on the right to an SZ-2 VCP.*

## 4. Updates to the SZ-2 Algorithm

As mentioned before, the SZ-2 algorithm has been implemented and is now operational providing significant reduction of obscuration (purple haze) at the lower elevation angles on the NEXRAD network. Although the initial algorithm recommendation was extensively tested in a research environment (Torres 2005), a number of issues arose during 2007, after its operational implementation. These are discussed next.

### 4.2. Fourth-Trip Overlaid Echoes

One significant issue reported from the field was related to noisy velocities observed by the KCRI radar in Norman, OK for two cases in June of 2007. The common thread in these two cases was the occurrence of 4$^{th}$ and 1$^{st}$ trip overlaid echoes. The reflectivity field shown in Fig. 3 can be used to verify that indeed, this is a case of 4$^{th}$ and 1$^{st}$ trip overlaid echoes with no significant 2$^{nd}$ or 3$^{rd}$ trips, a situation that may be common operationally, but that had not occurred before in our test cases. The corresponding Doppler velocity field is also shown in Fig 2 in which the patch of noisy velocities to the west of the radar is evident. With a little detective work, we can see that the patch of noisy velocities correspond to a 4$^{th}$-trip strong signal and a 1$^{st}$-trip weak signal; hence, the noisy velocities that we observe in the 1$^{st}$ trip correspond to weak-trip recovery.

In SZ-2, a processing notch filter (PNF) is designed to remove most of the strong-trip signal while leaving two replicas of the weak-trip modulated signal for further recovery. In the case of 1$^{st}$ and 2$^{nd}$ trip overlay (herein referred to as 1-2 overlay), the modulated weak trip has eight replicas, so a PNF that removes ¾ of the spectrum and retains ¼ is ideal. In the case of 1$^{st}$ and 3$^{rd}$ trip overlay (herein referred to as 1-3 overlay), the modulated weak trip has four replicas, so the PNF has to be adjusted to remove only ½ of the spectrum to retain the required two replicas. Finally, for the case of 1$^{st}$ and 4$^{th}$ trip overlay (herein referred to as 1-4 overlay), the modulated weak trip has eight replicas and, again, a ¾ notch is feasible. Fig. 4 depicts the placement and width of the PNF for the 1-2, 1-3, and 1-4 overlay situations. Also, this figure shows the spectrum of the re-cohered 2$^{nd}$ trip weak signal. Note that the main lobe corresponds to the true placement of the weak signal spectrum; however, there are decaying sidebands that do not bias the weak-trip velocity estimate but act as white noise, increasing the errors of estimates. Closer examination of one of the range locations with evident noise reveals that the recovered 1$^{st}$ trip spectrum (weak trip) does not seem to have the expected main lobe with decaying sidelobes! (see Fig. 5).

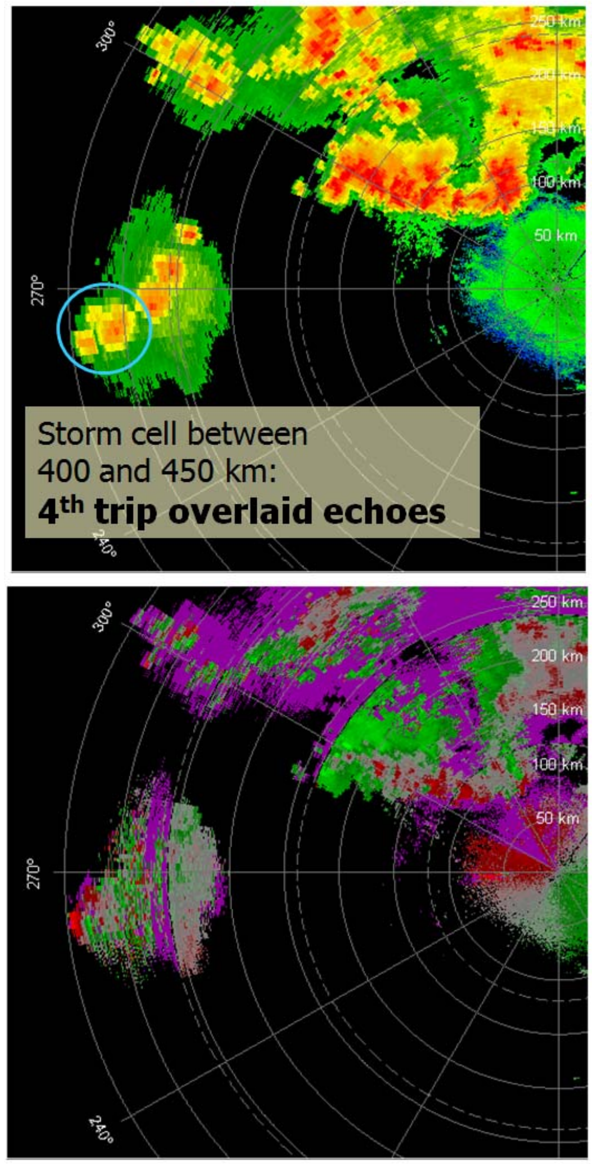



*Fig. 3. Reflectivity (top) and Doppler velocity (bottom) fields collected with the KCRI radar in Norman, OK on June 20, 2007.The maximum unambiguous ranges corresponding to the long and short PRTs are 471 and 119 km.*

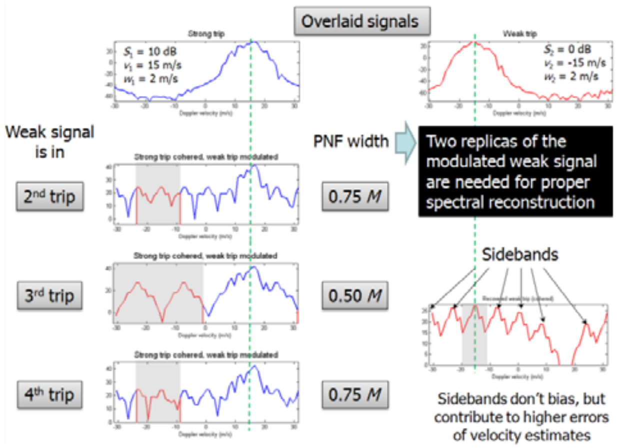



*Fig. 4. Application of the processing notch filter (PNF) for different overlay cases in the SZ-2 algorithm to reconstruct the weak-trip signal spectrum.*

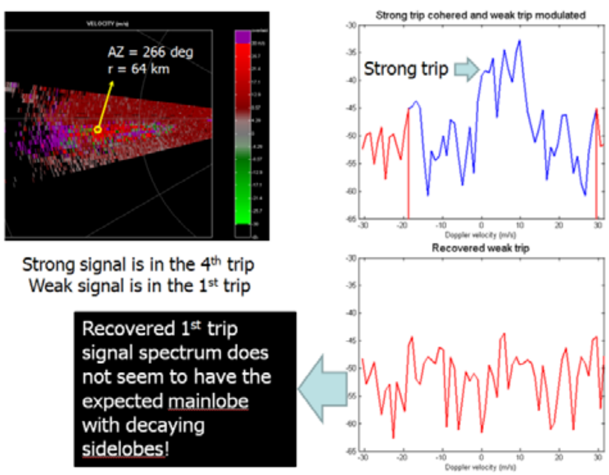



*Fig. 5. Spectra corresponding to a range gate with noisy velocity. The top-right panel shows the spectrum of the strong-trip cohered signal and the lower-right panel shows the spectrum of the recovered weak-trip signal.*

A closer look at the spectra of the recovered weak trip in the 1-2, 1-3, and 1-4 overlay situations reveals the key to this problem. Fig. 6 shows the spectra of the modulation phase codes before and after the application of the PNF. Whereas, the 1-2 and 1-3 overlay cases exhibit *decaying* sidebands, this is not true for the 1-4 overlay case. Further, a statistical analysis of the recovery of weak-trip velocities reveals that if strong and weak signals are 3 trips apart (e.g., $1^{st}$ and $4^{th}$ trips), recovery of the weak-trip velocity is not possible (i.e., errors of estimates are very large). This can be intuitively explained by computing the normalized spectrum width of the modulation code of the recovered weak trip signal. This number is a good indicator of the "spread" of the spectrum, which in turn is associated with the errors of velocity estimates. For the 1-2, 1-3, and 1-4 overlay cases, the normalized spectrum width ($\sigma_{vn}$) is 0.1855, 0.1855, and 0.5305, respectively. Hence, the normalized spectrum width in the 1-4 overlay case is about 3 times larger than in the 1-2 or 1-3 cases, which explains the much larger errors of estimates observed both in simulations and real data.

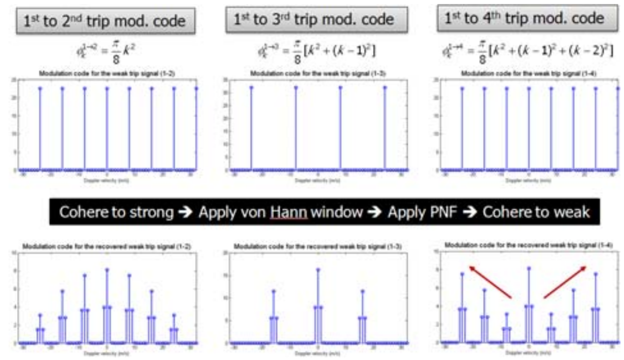



*Fig. 6. Spectra of the modulated code for the weak-trip signal and for the recovered weak-trip signal after windowing, notching, and re-cohering for different overlay cases.*

An easy solution to this problem consists on reducing the PNF notch width to reduce the normalized spectrum width of the modulation code of the recovered weak signal. A PNF notch width of $5M/8$ results in an even larger value, $\sigma_{vn}$ = 0.5610, whereas a notch width of $M/2$ (same as in the 1-3 overlay case) results in $\sigma_{vn}$ = 0.2637, which is much closer to the values observed in the 1-2 and 1-3 overlay cases. With this simple change, it is now possible to recover the weak-trip velocity if the overlaid signals are three trips apart.

In summary, proper recovery of the weak trip in the case of 1-4 overlay requires a processing notch filter narrower than initially assumed. This change is currently being implemented for future releases of the operational signal processing software. The change will improve the recovery of weak overlaid echoes in those cases where the strong-to-weak trip difference is three. Fig. 7 shows the same case in Fig. 3 processed with and without this change. It is evident that recovery of the weak $1^{st}$ trip velocities is now feasible. However, we can still observe noisy velocities in this and in other areas of the field. This issue is addressed next.

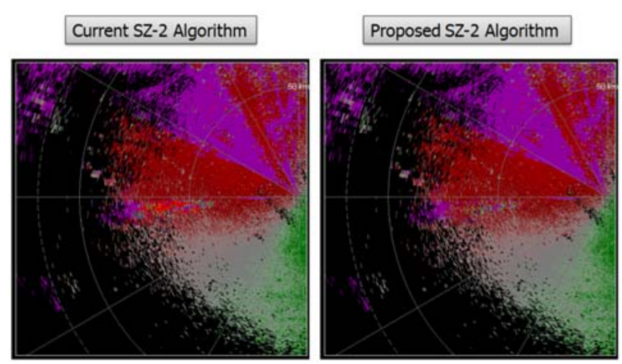



*Fig. 7. Doppler velocity fields for the June 20, 2007 case using the current and modified SZ-2 algorithms.*

### 4.3. Recovery Region Censoring

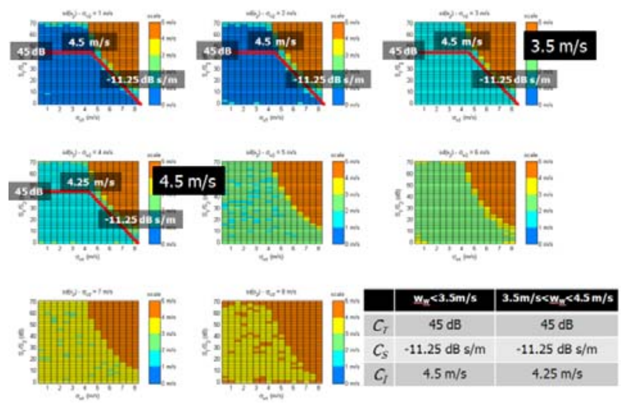
Since its operational implementation, Doppler velocity fields produced with the SZ-2 algorithm have been characterized by users as "noisier". On one hand, it was accepted that errors of weak-trip velocity estimates would be larger. In fact, never before had the NEXRAD system been able to recover Doppler velocities of weak-trip overlaid echoes. Due to the great operational gain associated with the SZ-2 algorithm, the NEXRAD Technical Requirement (NTR) for errors of weak-trip velocity estimates was waived. The normal requirement of standard errors of velocity less than 1 m/s for a true spectrum width of 4 m/s and a signal-to-noise ratio larger than 8 dB was changed to a maximum allowable standard error of 2 m/s. Nonetheless, it is apparent that the SZ-2 algorithm produces estimates with errors much larger than that (e.g., see Fig. 7).

A closer look at the weak trip number for the 06/20/07 case reveals that most of the noisy velocities come from the weak trip. Therefore, any censoring that should occur would be given by the power-ratio recovery-region censoring rules. Originally, the thresholds for this type of censoring were based on plots of errors of weak-trip velocity as a function of the strong-to-weak trip power ratio and the strong-trip spectrum width, with the weak-trip spectrum width as a parameter (Ellis et al. 2005). However, those plots only considered the 1-2 overlay case. A more thorough analysis is presented next.

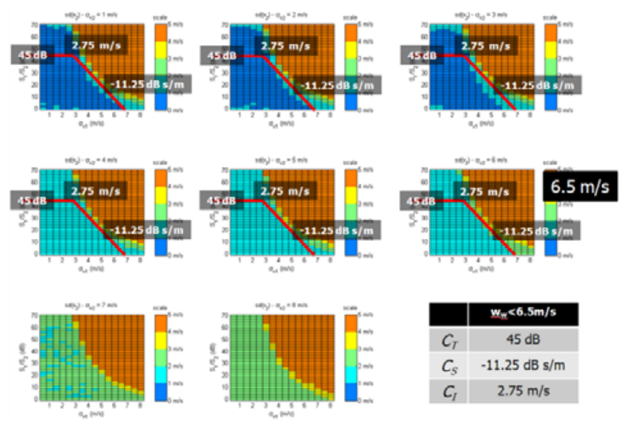
Fig. 8 shows the standard error of weak-trip velocity estimates on the strong-to-weak power ratio vs. strong-trip spectrum width plane, with the weak-trip spectrum width as a parameter (ranging from 1 to 8 m/s) for the 1-2, 1-3, and 1-4 overlay situations, respectively. These statistics were computed for the nominal transmitter frequency of 2800 MHz, a short PRT of 780 μs, and large SNR. Comparing these figures, it is evident that the different overlay situations exhibit different power-ratio recovery regions. Furthermore, for wide weak-trip spectrum widths, acceptable recovery of weak-trip velocities is not possible (i.e., errors of weak-trip velocity are unacceptably large).

Closer examination of these plots indicates that the current recovery region thresholds are not aggressive enough. We propose expanding the set of thresholds to accommodate all expected overlay cases and to modify the rules so that three weak-trip spectrum width regions are considered: narrow, medium, and wide. For the narrow and medium weak-trip spectrum widths, thresholds should be different, and for wide weak-trip spectrum widths, immediate censoring should be applied. Fig. 9 depicts the effects of the different censoring approach on the 06/20/07 case. Note that the current censoring scheme is not aggressive enough, producing a large number of noisy velocities. The proposed censoring scheme mitigates this problem but not completely. Evidently, we could apply an even stronger censoring scheme, but there is a trade-off between preserving data quality by censoring unreliable estimates and recovering as much as we can by not censoring valid data.

A comprehensive analysis is needed before establishing a permanent set of censoring thresholds. Ideally, we should examine a variety of cases collected from several operational radars. However, this type of analysis requires level-I phase-coded data which is not available. Whereas the determination of optimum censoring thresholds would take significant time, the SZ-2 code will be modified right away to include the upgraded rules for recovery region censoring. Having the additional functionality in place, the thresholds will be set so that the algorithm behaves exactly the same as in the current implementation. The thresholds will be updated in later releases after a thorough censoring threshold evaluation with little impact to the system. This would minimize the occurrence of noisy velocities when using SZ-2 at the expense of increasing the number of gates with purple haze.




*(a)*

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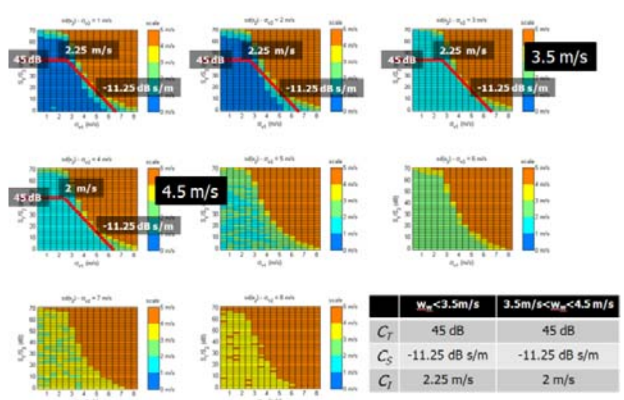


*(c)*

*Fig. 8. Standard deviation of weak-trip velocities for the SZ-2 algorithm as a function of the power ratio ($S_1/S_2$) and the strong-trip spectrum width ($\sigma_{v1}$) for the 1-2 (a), 1-3 (b), 1-4 (c) overlay cases, high SNR, and weak-trip spectrum widths ($\sigma_{v2}$) between 1 and 8 m/s.*

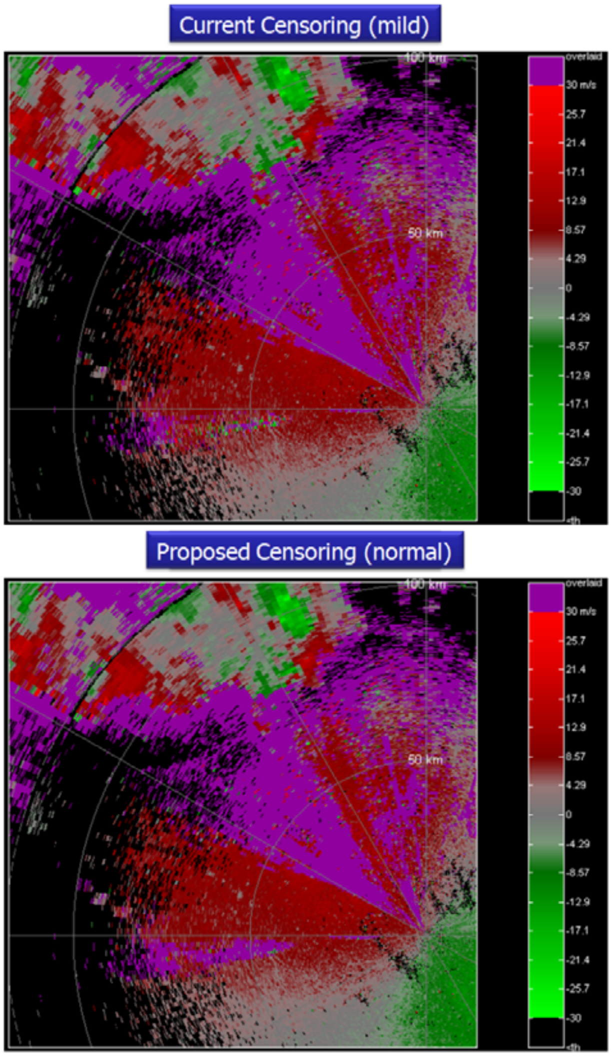


*Fig. 9. Doppler velocity fields for the June 20, 2007 case using current and proposed recovery region censoring threshold.*

## 5. Conclusions

This work demonstrated the performance of the SZ-2 algorithm as currently implemented on the NEXRAD network. Despite a few limitations and issues that arouse after the initial implementation, comparisons with previous "legacy" algorithms demonstrate the ability of the SZ-2 algorithm to effectively mitigate range and velocity ambiguities on the US network of weather surveillance radars.

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