

## P2.9 NEW SCIENCE FOR THE WSR-88D: IMPLEMENTING A MAJOR MODE ON THE SIGMET RVP8

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### 1. INTRODUCTION

Since the advent of the WSR-88D, 'purple haze,' the color that normally indicates unrecoverable range folded (RF) signals, has significantly obscured velocity and spectrum width fields in widespread weather. Meteorologists have often wished these range folded and velocity aliased ambiguous signals could be recovered. The National Severe Storms Laboratory (NSSL) developed the Sachidananda Zrnic (8/64) systematic phase coding algorithm (SZ-2) to help mitigate these ambiguities. This paper gives an overview of the problem, outlines the algorithm, discusses implementation details, and presents the results of the first signal processing effort to provide meteorologists with a solution to the range and velocity ambiguity problem.

### 2. THE NEW ORDA SYSTEM

Implementing signal processing algorithms to support new science is now possible because the Radar Operations Center (ROC), through the National Weather Service Office of Science and Technology with the help of RS Information Systems, just completed upgrading the fleet of WSR-88Ds with the Open Radar Data Acquisition (ORDA). This upgrade uses a commercial product, the SIGMET (part of Vaisala Group) RCP8/RVP8 system. This system is made up of the RVP8 Signal Processor/Digital Receiver, RCP8 Antenna/Radar Controller and Intermediate Frequency Digitizer (IFD). Both the RCP8 and RVP8 use the same chassis, I/O card, and PCI-based single board computer with dual Pentium processors running the Linux operating system (Cate, et al., 2003). Because of this

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*The views expressed are those of the authors and do not necessarily represent those of the National Weather Service.*

improved hardware, radar engineers have the processing power they need to implement new science. The discussion for this development focuses on the RVP8 software and hardware platform.

Another significant change from the original WSR-88D is the method for ground clutter filtering. Originally, the WSR-88D filtered clutter with a time-domain 5 pole elliptical filter. The ORDA signal processing introduced SIGMET's Gaussian Model Adaptive Processing (GMAP) clutter filtering. This frequency domain filter removes the clutter, and then attempts to rebuild any overlapping weather signals (Passarelli and Siggia, 2004) (Ice, et al., 2007). The clutter power removed is available as an output from GMAP. This feature is utilized in the SZ-2 algorithm. Frequency domain processing necessitates windowing the time series data. It was previously determined that the Blackman window provided the best clutter suppression for GMAP (Ice et al., 2004). This important detail has implications on the SZ-2 development.

### 3. OVERVIEW OF THE DOPPLER DILEMMA

The maximum unambiguous range is the farthest distance a transmitted pulse can travel from and return to the radar before the next pulse is transmitted, written as:

$$r_{max} = c / (2 PRF) \quad (1)$$

where  $r_{max}$  is the unambiguous range,  $c$  is the speed of light, and  $PRF$  is the pulse repetition frequency of the transmitted pulses. The maximum unambiguous velocity is the highest mean radial velocity or the largest pulse-pair phase shift that the radar can measure without ambiguity, defined as:

$$V_{max} = (\lambda PRF) / 4 \quad (2)$$

where  $V_{max}$  is the unambiguous velocity and  $\lambda$  is the wavelength of the pulse ( $\lambda \sim 10$  cm for the WSR-88D). Solving for  $PRF$  in both equations 1 and 2 and then equating them, results in the equation defining the Doppler Dilemma,

$$\begin{aligned}
 PRF &= c / (2 r_{max}) \quad \text{and} \quad PRF = (4 V_{max}) / \lambda \\
 c / (2 r_{max}) &= (4 V_{max}) / \lambda \\
 r_{max} V_{max} &= (c \lambda) / 8. \quad (3)
 \end{aligned}$$

Since the right side of the Doppler Dilemma equation (3) is constant for a specified wavelength, increasing  $r_{max}$  decreases  $V_{max}$ . For example, by decreasing the PRF to increase the maximum unambiguous range, then the maximum unambiguous velocity will decrease (WDTB, 2006).

#### 4. A WORD ON RANGE FOLDING

After each transmitted pulse, the radar starts 'listening' or sampling returns from that pulse. When transmitting with a high PRF, or a short time between pulses, the first transmitted pulse's returns are only sampled for a short total range. The second pulse is transmitted and sampling of its returns begins. However, the first pulse continues to travel through the atmosphere with echoes returning from scatterers beyond the unambiguous range. These echoes are added to the second pulse's returns. The returned echoes from the first pulse that are from beyond the unambiguous range are called second trip returns while the echoes from within the unambiguous range are called first trip returns. The combined first and second trip echoes are called overlaid or range folded echoes. In scans with a high PRF, allowing for higher velocities to be detected, range folding is widespread and velocities from those areas must be recovered from overlaid signals.

#### 5. OVERVIEW OF CURRENT RECOVERY OF RANGE FOLDED SIGNALS

The current scanning strategy to recover both long range and high velocity returns for the WSR-88D at the lower elevation angles is the split-cut scan. It consists of two sweeps at the same elevation angle, each with a different PRF. The first sweep, known as the Surveillance scan, is optimized to recover reflectivity at long distances by using a low PRF (e.g., 320 Hz or 3.1 ms between pulses). The second sweep, known as the Doppler scan, is optimized to recover high velocities and wide spectrum widths by using a high PRF (e.g., 1013 Hz or 987  $\mu$ s between pulses). The low PRF scan can have an unambiguous range up to four times greater than that of the high PRF scan. Accordingly, the maximum unambiguous velocity for the high PRF scan can be up to four times greater than that of the low PRF scan. Since the Surveillance scan is not likely to contain overlaid echoes, it provides the 'truth' information of the placement of the weather for the velocities from the Doppler scan that are overlaid. The current range unfolding algorithm can only recover one of the overlaid signals, if any at all. The velocity is deemed recoverable if one of the powers from the Surveillance scan that correlate to the overlaid signal is much stronger than the others.

#### 6. OVERVIEW OF SZ-2

The SZ-2 algorithm provides a more sophisticated method to recover overlaid data by changing the phase of (or phase coding) each transmitted pulse of the Doppler scan with a systematic sequence known as the switching code (Sachidananda, et. al., 1998). This phase coding scheme provides a method to separate overlaid signals in the spectral domain. For example, if there is only first trip signal in the return, the switching code is subtracted to give the cohered first trip signal from which moments are recovered normally. However, if there is second trip signal added to the first trip signal due to range folding, cohering for the first trip by subtracting the switching code aligned with the transmission pulse recovers first trip, but not all the phase shift is removed from the second trip signal. The remaining phase shift in second trip is called the modulation code. The modulation code evenly distributes the second trip signal across the Doppler frequency interval in eight replicas of the fully cohered second trip signal. Therefore, the second trip signal does not significantly bias the first trip velocity calculation. Third and fourth trip overlaid signals may be recovered as well. However, the algorithm is limited to recovering a maximum of two trips out of a total of four possible overlaid trips.

The SZ-2 algorithm follows the current WSR-88D scan strategy by using two sweeps at the same elevation (thus the "2" in SZ-2); (1) a Surveillance scan to use as 'truth' data to aid in the proper placement in range of the higher velocities from (2) a high PRF, phase coded Doppler scan.

When attempting to recover overlaid signals, it is necessary to process and then remove the stronger of the two overlaid signals before attempting to process the weaker signal. A strong return, or strong trip, is not always in the first trip. Similarly, a weaker return, or weak trip, is not always in the second trip. Often, the stronger of the two overlaid signals is beyond the unambiguous range. Therefore, strong trip does not imply first trip and weak trip does not imply second trip.

The SZ-2 algorithm is summarized by the following steps:

1. **Cohere to strong trip** by subtracting switching code.
2. **Recover strong trip moments:** reflectivity, velocity, and spectrum width.
3. **Go to frequency domain** by applying a Fourier Transform.
4. **Notch out strong trip** centered on the velocity of the strong trip. This removes the strong trip competing power leaving two replicas of the modulated weak trip signal.
5. **Return to time domain** by applying an Inverse Fourier Transform.
6. **Cohere to weak trip** by subtracting the modulation code that coheres from strong trip to weak trip.
7. **Recover weak trip moments:** power (used in censoring only) and velocity. Spectrum width for the weak trip comes from the Surveillance scan.

8. **Properly place moments** using the Surveillance scan data to place recovered strong and weak trip reflectivity and velocity into proper first and second trip. Use calculated spectrum width from strong trip. For weak trip, use the spectrum width from the Surveillance scan (Saxion, et al., 2005) (Zrnic, et al., 2006).

## 7. TRANSITIONING FROM SCIENTIFIC TO OPERATIONAL ENVIRONMENT

The NSSL provided the ROC with a functional description of the SZ-2 algorithm (pseudo-code). They also developed and tested the algorithm in MATLAB. This provided a solid starting point for ROC engineers to implement SZ-2 in the RVP8. While the MATLAB implementation provided a good research tool for validating the algorithm, once operational in the complex environment of an actual radar and under the scrutiny of meteorologists, two issues became apparent. The first was the realization that the use of clutter filtering in all bins is a widespread method for managing clutter by meteorologists in the field (Chrisman and Ray, 2007) (Ray and Chrisman, 2007). We discuss this in detail in the following paragraph. The second was the impact of the subtle difference in the change of the meaning of 'purple haze,' or RF censoring, between the standard ORDA Frequency Domain Processing and SZ-2 processing. The solution to this was defining and implementing the censoring rules in the proper order within the SZ-2 algorithm and within the SIGMET RVP8 software architecture.

Separating weather signal returns from ground clutter has long been a challenging process. With the addition of phase coding, clutter filtering becomes even more challenging for the SZ-2 algorithm. If clutter exists in two or more trips, SZ-2 cannot separate any of the overlaid weather signals and therefore flags the bin as overlaid, or purple. The only way the implemented SZ-2 algorithm knows whether or not to clutter filter a specific range bin is by the clutter map provided by the ORDA high-level software. Originally, if an operator has specified clutter filtering in all bins, then SZ-2 assumed that clutter existed in all bins. The unacceptable results were that almost all bins were censored in all trips. SZ-2 was supposed to reduce RF censoring, not increase it! Since clutter filtering in all bins is widely used in the field, this issue had to be addressed.

A simple solution devised by the NSSL was to test if clutter really did exist in more than one trip when the clutter map indicated that it did. SZ-2 checks clutter power removed by the GMAP clutter filter during the Surveillance scan to see if clutter was actually removed from that bin by comparing it to a predefined threshold. If so, then clutter filtering is applied to this bin in the Doppler scan. While this helps, it is not a perfect solution. Ground clutter is not reliably detected with this method, so clutter filtering is not applied in some cases. This results in a velocity estimate that is biased towards zero. An improved solution, the Clutter Mitigation Decision algorithm (CMD), is currently in development (Ice et al., 2007).

## 8. OVERVIEW OF SZ-2 MAJOR MODE STRUCTURE

The ROC engineers' task was to implement the SZ-2 logic on the RVP8, the ORDA subsystem that performs the majority of the real-time signal processing for the WSR-88D. The RVP8 organizes different signal processing techniques within Major Modes. The ORDA uses the SIGMET provided FFT (Fast Fourier Transform) and Batch Major Modes. The RVP8 software environment provides a clean method for inserting customized signal processing software via a Major Mode. The first new science signal processing Major Mode for the WSR-88D is the SZ-2 algorithm.

Major Mode software has an organized directory structure such that externally developed software is completely separate from, but integrated with, SIGMET release software. This way, the developer can upgrade SIGMET software without having their work be affected by the install process. The RVP8 Major Mode infrastructure software is written in C with Intel Integrated Performance Primitives for high speed computationally intensive functions like FFT, convolution, filtering, dot product, etc. The Major Mode software is controlled by high level software such as ascope or IRIS (SIGMET products), ORDA controlling software, or by third party applications, such as our trimmed down process driver (pd) (Rhoton et al., 2005).

SIGMET's hardware and software organization allows for a separation of the processing software from the underlying hardware. First, it provides access into the layers of the controlling software and access to the time series data. The two layers of significant importance to this project are the RVP8 main thread (rvp8main) that controls the setup, configuration, system triggers, and controlling of the RVP8 processing thread (rvp8proc) that performs scientific processing for RVP8. Rvp8main forks N identical code copies of the rvp8proc software providing parallel processing options for faster throughput. Second, SIGMET provides communication between the rvp8main thread and the rvp8proc threads, as well as between the multiple rvp8proc threads via shared memory. Shared memory management is provided by SIGMET. Third, the developer may change all or part of the SIGMET provided Major Modes by copying to the development tree and modifying relevant portions. Unchanged SIGMET routines remain in the SIGMET tree and may be called as needed. SIGMET's rvp8proc code is available to developers as source code, providing a substantial foundation on which to build new signal processing software. And finally, custom opcodes are provided for real-time communication to a Major Mode from the high level controlling software outside the RVP8.

In addition to the strong software infrastructure, SIGMET provides a rich debugging and testing environment for RVP8 processing software by providing windows through which a developer may see how the RVP8 software interacts with high level controlling software or the low level support software. Some of these tools include methods for showing 1) SIGMET specific and custom opcode communications (SIGMET, 2006, RVP8 Users Manual Chapter 5), 2) live acquired pulse information from the RVP8 receiver card to the rvp8main thread, 3) blocks of acquired pulses selected

for computations as one radial, and 4) real time callback timers. The SZ-2 development derived valuable insights from viewing the opcode communications and seeing which blocks of pulses were selected for computation of a radial.

## 9. RESULTS

The following images are from the last stages of a widespread stratiform rain event collected on March 19, 2006 at 02:27Z. ROC engineers collected the data from KCRI, the test radar in Norman, OK, using a test Volume Coverage Pattern (VCP) that was modified from VCP11. To modify the VCP, we replaced the 1.5° split

cuts with 0.5° SZ-2 split cuts (one Surveillance scan followed by a Doppler SZ-2 scan). The modified VCP continues with batch cuts at 2.4° elevation angle. This means that the processing of the ORDA and the SZ-2 scans, at the same elevation angle, are separated only by the time it takes to perform a split cut. All images in this paper were generated using a playback process that allows the ROC engineers to change processing parameters such as those for clutter filtering.

The widespread nature of this rain event shows SZ-2 at its best. Figure 1 is the Surveillance scan reflectivities. All images noted in this paragraph are processed using a bypass map for clutter filtering.

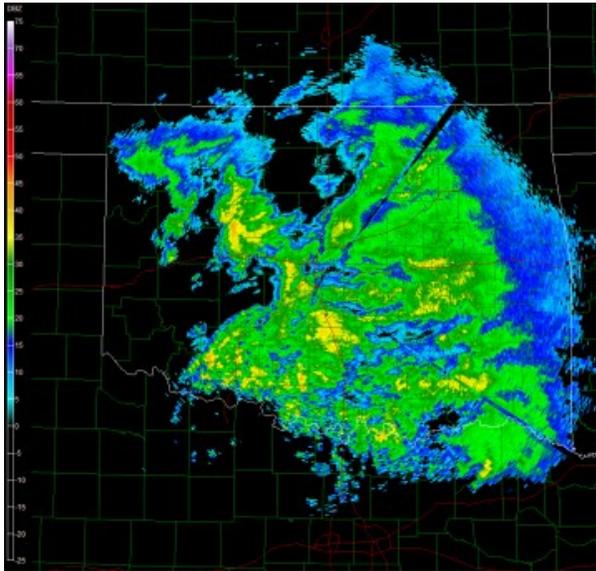


Figure 1 Surveillance Scan Reflectivity, Bypass Map

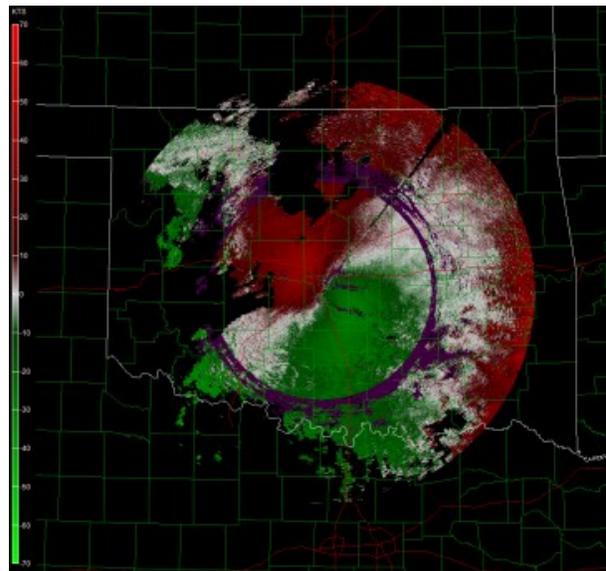


Figure 3 SZ-2 Velocity, Bypass Map

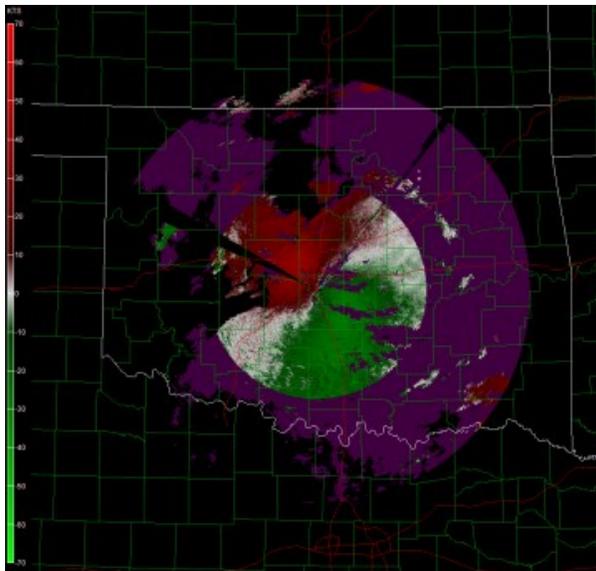


Figure 2 ORDA Processed Velocity, Bypass Map

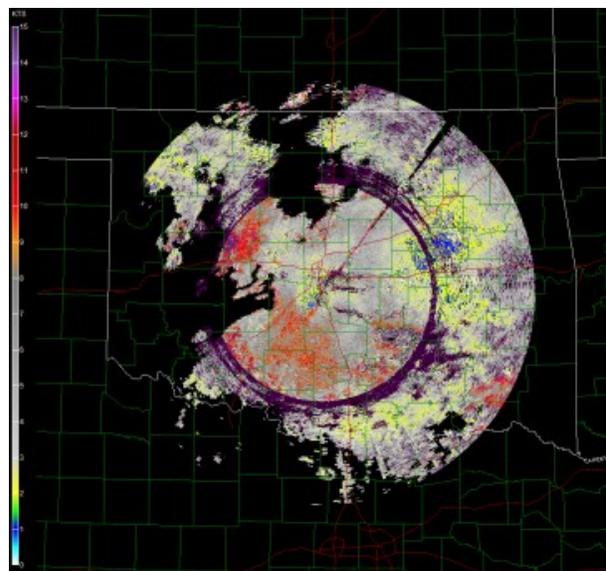
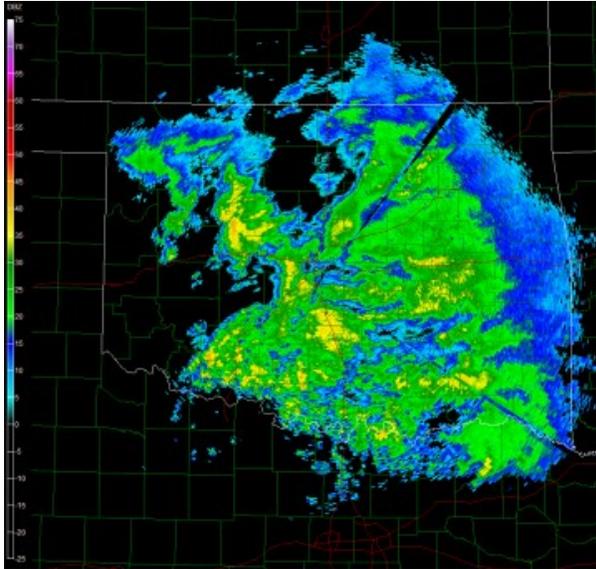
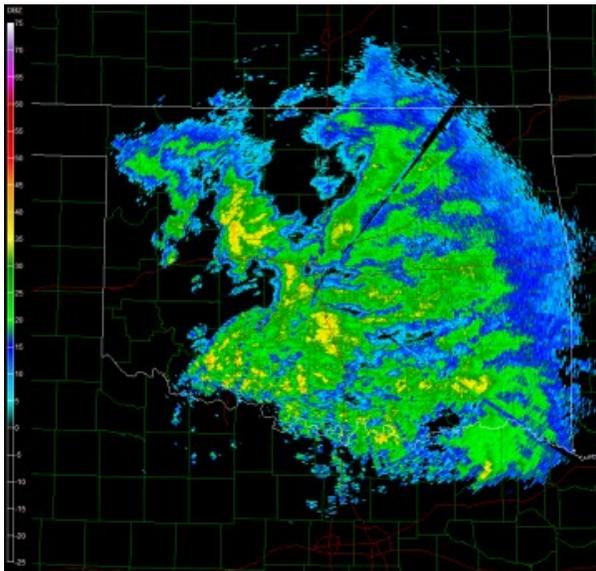


Figure 4 SZ-2 Spectrum Width, Bypass Map



**Figure 5 Surveillance Reflectivity, Bypass Map**



**Figure 6 Surveillance Reflectivity, All Bins**

Figure 2 shows baseline ORDA Doppler scan velocities. Note the large amount of unrecoverable overlaid returns (indicated by 'purple haze') especially in the second trip. Figure 3 shows the SZ-2 velocities with previously overlaid velocities recovered. Spectrum width from SZ-2 processing is shown in Figure 4.

Section 7 discussed the effect that all bins clutter filtering had on the SZ-2 development. While the current solution is the best available at this time, all bins clutter filtering still has noticeable impacts on the SZ-2 processing. It is important that meteorologists understand the impact of all bins clutter filtering on moment estimation. In Figures 5, 6, 7, 8, and 9, the images are generated from the same data set from March 19, 2006, but processed with either a bypass map or all bins clutter filtering.

The impact of all bins clutter filtering on reflectivity estimates behaves the same for SZ-2 as it does for ORDA processing. Reflectivity is reduced in areas of near zero velocities (Ice et al., 2007). Note that Figure 5 that shows processing with a bypass map has areas with higher values for reflectivity in the Northeast section compared to the all bins processing presented in Figure 6. This area of low values in Figure 6 corresponds with returns having velocities near zero, so GMAP, assuming it is clutter, removes that signal, thus reducing the reflectivity estimates.

All bins clutter filtering impacts SZ-2 velocity estimates more than it does ORDA processing because only one trip with overlaid clutter can be recovered. Therefore when all bins clutter filtering is requested, SZ-2 attempts to decide if clutter actually exists. The first difference is the number of zero velocities. Note the number and placement of zero velocity data with SZ-2 processed data and bypass map in Figure 7. Figure 8 shows SZ-2 velocity processed with all bins clutter filtering. Notice the increased number of zero velocities near the radar. However, the number of zero velocities is comparable to Figure 7 in the rest of the field. Figure 9 shows the ORDA processed velocities with all bins filtering. In ORDA processing, the clutter filter is applied to every bin without checking to see if clutter exists there or not. Note the clutter near the radar is removed, however, so are many of the zero velocities in the rest of the field (note the Northeast section). This behavior has been observed and studied previously (Ice et al., 2007).

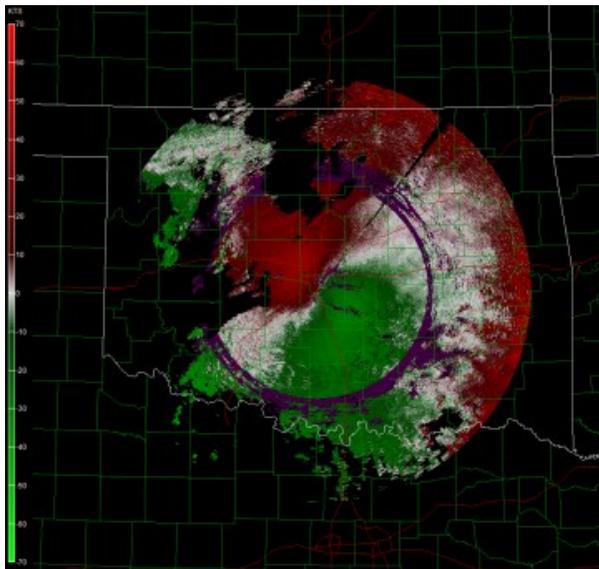
Another difference between SZ-2 processed with all bins and SZ-2 processed with bypass map is the ring of purple at the unambiguous range. This ring is sometimes referred to as the clutter ring, is characteristic of SZ-2, and corresponds in the second trip to the first trip region of strong clutter near the radar. In Figure 7, the clutter ring is wider and the velocities surrounding it are spatially smooth. In Figure 8, the clutter ring is smaller, but there are noisy velocities interspersed. When a bin with clutter is not filtered, then it is not detected as overlaid, and the bin is not colored purple. In addition, the algorithm estimates velocity from this clutter contaminated bin for weak trip which results in noisy estimates in that trip.

The last difference is the slight increase in the number of noisy velocities in first trip in the SZ-2 velocities with all bins clutter filtering (Figure 8). Notice the brighter green velocities near the radar to the East and a few noisy velocities to the North. This could be due to the application of the Blackman window on the time series data before clutter filtering.

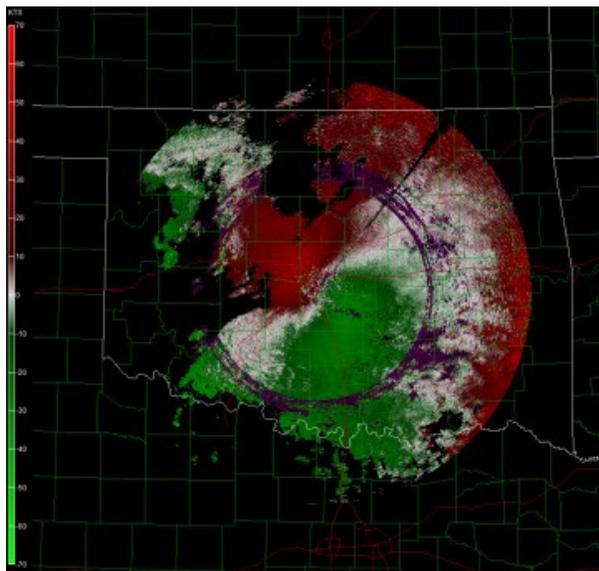
## 10. CONCLUSIONS

Transitioning from a scientific algorithm to operational software requires an understanding of the algorithm, the host platform, and the radar, as well as in depth testing. Through this effort with the support of many organizations, the WSR-88D will host the first new science range/velocity mitigation algorithm, SZ-2. SZ-2 provides significant improvement in the recovery of overlaid returns allowing for meteorological analysis of overlaid trip velocity and spectrum width estimates. Due

to the complex nature of the algorithm, it is important to understand how to maximize the performance of SZ-2. One way to achieve this is by limiting the use of all bins clutter filtering.



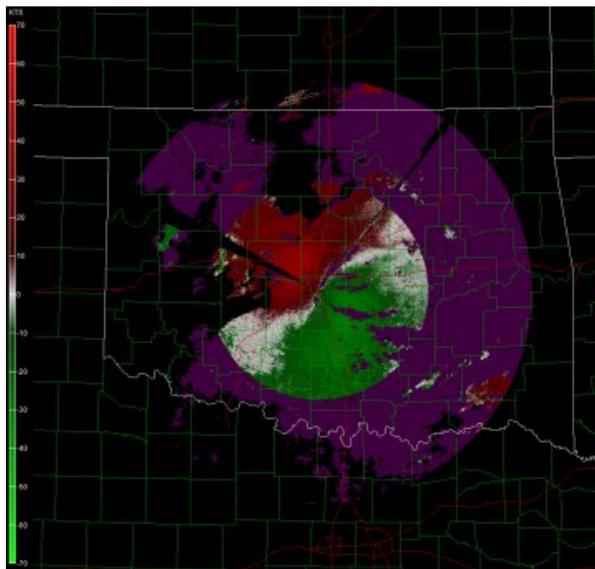
**Figure 7 SZ-2 Velocity, Bypass Map**



**Figure 8 SZ-2 Velocity, All Bins**

## 11. ACKNOWLEDGEMENTS

The ROC Engineers were able to accomplish this only through the help of NSSL, the National Center of Atmospheric Research, the ROC Data Quality Team, SIGMET Engineers, and ROC Systems Engineers. Thank you all for sharing your knowledge, skills, and expertise so generously.



**Figure 9 ORDA Velocity, All Bins**

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