3 ENHANCING THE FOUNDATIONAL DATA FROM THE WSR-88D:
PART II, THE FUTURE

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1. INTRODUCTION

This paper is about the future. It describes practical ideas, many proven very recently, that have potential for enhancing the foundational data from the WSR-88D Doppler Weather Radar. It is forward looking, and intended to aid program stakeholders as they sustain and improve operations for this critical national weather asset. It follows the spirit of earlier visionary work that has made the radar a success (Elvander, 2001).

For most of the twenty plus years of the WSR-88D's lifecycle, the Radar Operations Center (ROC), formerly Operational Support Facility (OSF), has conducted data quality improvement projects. This program, conducted under a Data Quality Memorandum of Understanding (DQ MOU) in partnership with the National Severe Storms Laboratory (NSSL), the University of Oklahoma, and the National Center for Atmospheric Research (NCAR), has resulted in several major signal processing improvements to the radar (Saxion, 2011). Notable among these improvements are mitigation of the classic Range Velocity Ambiguity problem and automatic identification and removal of clutter. Improvement in the basic quality of the radar moments has been achieved, and the ROC is about to deploy a new hybrid spectrum width estimator which will support the aviation application (Meymaris, 2009).

The program also established a significant infrastructure for capturing, processing, and archiving the digital output of the radar receiver. This capability has been the key to the rapidly increasing pace of signal processing improvements, and also formed the basis of all engineering evaluations aimed at ensuring new signal processing features meet or exceed system requirements. The infrastructure resulting from the data quality program was key in the recent evaluation and resulting approval of the polarimetric upgrade now set for deployment.

There have been many surveys regarding the future of weather radar that addressed signal processing improvements (Fabry, 2003, Keeler, 1990, National Academy of Sciences, 2004, Snow, 2003, Zrnic, 2003). Engineers at the Radar Operations Center routinely survey published research and maintain contact with experts in the field in order to plan future upgrades and ensure modifications can support continued growth in capability.

This paper presents a brief overview of some possibilities in the next section. The paper then focuses on four areas that are of interest because of their potential impact or their state of development, making implementation practical.

2. POTENTIAL TECHNOLOGIES

The range of possible improvements is quite expansive. They range from methods to enhance system sensitivity (Ice, 2011, Melnikov, 2011) to advanced spectral reconstruction using multiple radar waveforms on separate scans (Warde, 2012). Melnikov demonstrated that some usable weak signals can be recovered by simply lowering the signal to noise threshold and then removing the resultant non-meteorological data with an improved speckle detector. The use of coherency estimates as a means for adaptively setting the signal to noise threshold has also been demonstrated (Ivic, 2009).

Warde proposes a technique that combines the spectra from the surveillance and Doppler scans to reconstruct an ideal, unambiguous range-Doppler spectrum that can be then used to estimate velocity and spectrum width. Even more sophisticated spectral decomposition and analysis techniques are likely possible as signal processing hardware and software advances. Perhaps analysis methods, used in other disciplines, such as empirical mode decomposition with Hilbert transforms will prove useful (Huang, 1998).

The growing use of wind turbines for generating electricity in the United States, while beneficial for the most part, negatively impacts weather radar operations. The moving blades represent very

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large targets that feature motion induced Doppler shifts. This results in signal spectra that are very much like weather returns and thus are difficult for the clutter filters to remove. Research continues into means of identifying and removing this clutter, and new techniques will likely be developed and implemented (Hood, 2010).

More advanced techniques may not prove necessary or possible unless they are part of a planned service life extension program involving hardware upgrades. One example is pulse compression which could enable use of solid state transmitters. Until recently pulse compression was not a mainstay of meteorological radar, due mostly to the high range side lobes resulting from the compression filtering process. This has largely been overcome with advanced signal processing and special pulse coding schemes. Some researchers are beginning to focus on practical implementation of pulse compression and even developing algorithms based on simulated pulse compression data (Alberts, 2011).

The authors identified four enhancements that are important in the near term, or are sufficiently mature to merit serious consideration for operational development. These are: (1) Polarimetric Data Quality Improvements, (2) On-Line Determination of the System Noise Level, (3) Clutter Environment Analysis using Adaptive Processing, and (4) Oversampling and Adaptive Psuedowhitening.

3. POLARIMETRIC DATA QUALITY IMPROVEMENTS

The NEXRAD program, through the National Weather Service Office of Science and Technology has been managing the development and deployment of a polarimetric upgrade to the WSR-88D. Working with the prime contractor, L3/Stratis, and the technical subcontractor, Baron Services, the team has guided the project to the point that deployment has been approved for the Fall of this year, 2011. The upgrade provides basic polarimetric capability in the Radar Data Acquisition (RDA) subsystem, and produces three basic dual polarization variables. These are Differential Reflectivity (ZDR), Correlation Coefficient (RHO), and Differential Phase (PHI).

The upgrade also features a modified version of the Gaussian Model Adaptive Processing (GMAP) clutter filter based on the one in current use in the fielded systems. The filter has been modified in order to preserve the differential information between the horizontal and vertical channel data, but is at this point a fairly simple approach and is not optimal.

While the upgrade performs well, and supports all system level requirements, it is not optimized given that the polarimetric research was conducted on non-operational systems. The research community was able to explore the performance of dual polarization using custom scanning strategies and radar waveforms. The operational version to be deployed is constrained by the realities of current waveforms and scanning strategies, and in many cases is hampered by a limited number of samples for obtaining the estimates. There are three main areas for potential improvement. These are: clutter filtering, calibration, and moment estimation.

Prior to the start of the upgrade design, there was scant research available on the topic of clutter filtering for dual polarization variables. What research was done focused mainly on the impacts of clutter on the estimates (Friedrich, 2009). Some of the basic research is quite recent (Hubbert, 2009a, 2009b, 2011). The Radar Operations Center was asked to provide a recommendation for filtering that the contractors could implement. After consultation with the National Severe Storms Laboratory, the government engineers recommended the simple approach that is currently implemented. This design merely uses the number of clutter coefficients removed by GMAP from the horizontal channel to establish the number of coefficients to be removed from the vertical channel. Then the usual spectral reconstruction feature of GMAP is disabled. This simple approach attempts to preserve the spectral component relationship between the two channels. However, it is limited in performance, especially if the clutter has polarimetric characteristics and does not behave in a standard way. Figure 1 shows how the ZDR of clutter can bias the weather ZDR estimate for various levels of the clutter to signal ratio (Scott Ellis, NCAR).

Improved techniques for recognizing clutter contamination using dual polarization variables are possible, and even being implemented in near term software releases. The Radar Operations Center is preparing a new version of the Clutter Mitigation Decision (CMD) algorithm based that incorporates the new polarimetric data. This upgrade is based on research at NCAR. Figure 2 depicts an example of the characteristic differences between weather and clutter. This figure shows the standard deviation of ZDR for both weather and clutter signals. Also shown is a fuzzy logic membership function that is a component of a clutter identification algorithm (Scott Ellis, NCAR). The program should continue to follow developments in clutter filtering for dual polarization and the ROC should evaluate all new techniques, implementing them as appropriate.

The most challenging technical issue with an operational dual polarization system is calibration. In particular, the major calibration problem is determining the radar system's contribution to the estimated value of ZDR. This "System Differential Reflectivity" is a component of the measured ZDR and serves to mask the true ZDR of the radar return signal. System ZDR comes from imbalances between the radar hardware channels, and has components related to imperfectly divided transmitter power, mismatched transmission lines such as waveguides, errors in the antenna, and differences in the gains between the two receiver channels. Calibration consists of accurately determining the System ZDR contributions of all these components.

The contractors have implemented a sophisticated set of engineering type measurements aimed at determining the System ZDR to the desired uncertainty of 0.1 dB. It is no small challenge to meet this goal using microwave metrology methods, but experimental measurements and mathematical analysis indicates this can be achieved with the developed method. The government team has been engaged in various efforts to independently verify this performance, focusing on external measurements using precipitation, ground clutter, and solar scans. Indications are that the use of precipitation will require long term data collection and analysis and that it is not possible to assess the calibration state of a given radar using only one, or a few, rain events.

Engineers at NCAR developed a method based on cross polarization power measurements, from either precipitation or clutter, coupled with solar scans (Hubbert 2003 and 2007). The engineering team at the ROC and NCAR are implementing this method as a means of verifying system performance and potentially as a field capable calibration method. Figure 3 is an example of the use of solar scans to monitor system performance (Mike Dixon, NCAR).. These are scans of the sun's disk showing noise power received in both the horizontal and vertical channel. Figure 4 is a plot of the difference in the noise power from each channel and shows that the difference in the horizontal and vertical channel power is quite uniform over the inner circle which represents the one degree main beam of the antenna (Mike Dixon, NCAR). The small difference shown (about 0.3 dB in this case) represents the mismatch between the channels in receive mode, and includes the antenna, transmission lines, and receiver gains. This data, combined with the two way data from using the transmitter and scanning ground clutter, can be used to yield an independent method of measuring System Differential Reflectivity. The ROC should continue to monitor developments in calibration research and evaluate appropriate methods.

One of the realities of implementing new science into existing systems is that there are limitations on system operations. There are mechanical operating limits on the antenna positioning hardware for example. A major limitation is the requirement for timely radar volume updates. These limitations are usually not present in a research environment where the goal is to find out what is possible from the basic science. The dual polarization project is no different in this regard. System managers have to adopt the science derived signal processing to the realities of the field. A prime example is the limited number of pulse samples available for obtaining the estimates. In the case of Volume Coverage Pattern 12, only 15 samples are available on the Surveillance Scan from which the three polarimetric variables are estimated. This is an area ripe for investigation.

4. ON-LINE DETERMINATION OF THE SYSTEM NOISE LEVEL

One very critical measurement is the overall system noise level. Because estimates are derived from noise adjusted power measurements, errors in system noise estimation can seriously degrade the quality of the dual polarization variables, especially ZDR and RHO in low signal to noise conditions. The current baseline method consists of simple taking many power samples with the antenna at a high elevation angle at the end of each Volume Coverage Pattern. This is a single measurement, adjusted for elevation, but is not azimuth dependent. The evaluation teams have noted errors in this method that affect data quality. NSSL scientists have developed a new method for estimating noise that uses data from each azimuth and derives the noise from the actual position from which the radar data is obtained (Ivic, 2011). The left image in Figure 5 shows the ratio of the on-line radial estimate of noise to the single baseline estimate as a function of azimuth for both the horizontal and vertical channel (Igor Ivic, NSSL). Note the considerable variation in noise power by azimuth. Also notable is the obvious error in the vertical channel. The right side of Figure 5 shows a reflectivity scan and depicts the difference in the data obtained from both methods (Igor Ivic, NSSL). Bins marked in white are weak returns that were added by use of the new radial method.

5. CLUTTER ENVIRONMENT ANALYSIS USING ADAPTIVE PROCESSING

One very promising new method for managing clutter contamination is currently implemented on the National Weather Radar Testbed (Warde, 2009b). The Clutter Environment ANalysis using Adaptive Processing (CLEAN-AP) was developed at the University of Oklahoma, Cooperative Institute for Mesoscale Meteorological Studies, National Severe Storms Laboratory, and has been shown to meet basic WSR-88D requirements. The NEXRAD Technical Advisory Committee (TAC) has recommended that the ROC perform an engineering evaluation of CLEAN-AP for possible implementation in a future software release.

Figure 6 shows the performance of CLEAN-AP on the National Weather Radar Testbed as it removes anomalously propagated clutter. The small inset shows the same data case from the Oklahoma City NEXRAD for comparison (Dave Warde, NSSL). Figure 7 depicts all three base radar moments for a mesocyclone case with CLEAN-AP on and off. Note that while CLEAN-AP removes the ground clutter, the data in the mesocyclone region is unaffected.

The ROC team plans to implement an engineering version of CLEAN-AP for the WSR-88D as soon as resources permit.

6. OVERSAMPLING AND ADAPTIVE PSUEDOWHITENING

The final technique featured here is oversampling and whitening, a method that has been known for some time, but had undergone several evolutions aimed at making it practical to implement (Curtis 2011a, 2011b, Torres, 2009, Yu, 2006). This method takes multiple samples in the receiver within the pulse duration time. The technical details of this method are not addressed here, but it is essentially a method for transforming highly correlated samples into a set of samples that are less correlated and thus more independent. The decorrelation process is the key, but can be computationally complex. The Adaptive Psuedowhitening algorithm overcomes prior limitations, making it a practical candidate for implementation. The net result will be increased accuracy of estimates within the same, or even faster, update time constraints. This method is directly applicable for improving the quality of the polarimetric variables.

Figure 8, from Curtis, 2011b, shows reflectivity and velocity data processed by the current matched filtering method compared to two versions of oversampling. In the top panels, the baseline method, 16 samples were used for reflectivity and 64 were used for velocity. In the bottom panels, only 12 samples were used for reflectivity and 26 were used for velocity. This sample clearly shows the rapid update advantages of oversampling. ROC engineers have calculated that with oversampling rapid update VCPs could be used that would take advantage of the fastest rotation speeds the pedestal can reliably support while improving data quality. When combined with other optimization methods such as Automatic Volume Scan Early Termination (AVSET), volume update times approaching 2 minutes may be possible.

7. THE FUTURE

The future for the WSR-88D and the United States meteorological radar program is bright with no technological barriers in view. The explosion of fast computing coupled with major advances in analysis and software development has made once impossible tasks almost routine. The improvements possible to the critical foundational radar data will be only limited by available resources.

Promising research continues, and even accelerates. The WSR-88D Radar Operations Center team members plan to continue the work under the proven framework of the DQ MOU (Saxion, 2011).

The National Center for Atmospheric Research is implementing a sophisticated local radar research network in the front range of Colorado in partnership with Colorado State University. They are relocating the base of the S-Pol radar in order to enhance performance and better position it for multiple radar experiments with CSU CHILL and the regional WSR-88D units in Denver and Cheyenne. The NCAR team is well positioned to provide significant improvements to the signal processing of polarimetric variables. They have devoted considerable effort to characterizing the effects of antenna errors, scattering, electromagnetic propagation, and clutter contamination on dual polarization variable quality (Hubbert, 2011).

The National Severe Storms Laboratory and the University of Oklahoma continue their work on the National Weather Radar Testbed phased array system. This latter project has yielded many of the signal processing improvements described herein and will continue to provide valuable support to the NEXRAD program (Torres, 2011). Their science and engineering team continues to work on near term enhanced range velocity ambiguity mitigation improvements such as Staggered PRT. There are pending updates to this signal processing method that can be incorporated in the near term as the Radar Operations Center implements Staggered PRT as part of already planned deployments. The performance in range overlaid situations can be improved and a method is identified (Warde, 2009a). Research at the University of Oklahoma and the National Severe Storms Laboratory has also identified new radar moment estimators using multiple lag processing (Lei, 2009).

This paper is not intended to prescribe specific programs or a list of techniques to implement in the near term. Rather it is intended as a resource for those charged with guiding the program through the next decade or so as the radar ages and undergoes a planned service life extension. The authors hope is that this will stimulate bold thinking in this regard and the goal is to ensure the radar evolves with the demand for increasing services in a time of shrinking resources. There is no technical barrier preventing the radar from serving the public for the next twenty years in the same excellent manner as it has over the past twenty.

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Appendix – Tables and Figures

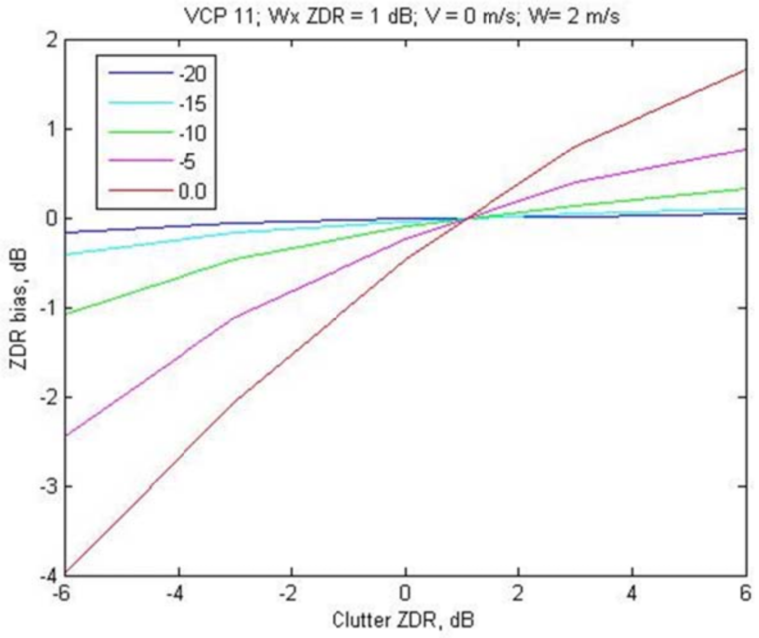

Figure 1 – Effect of Clutter on ZDR Estimates

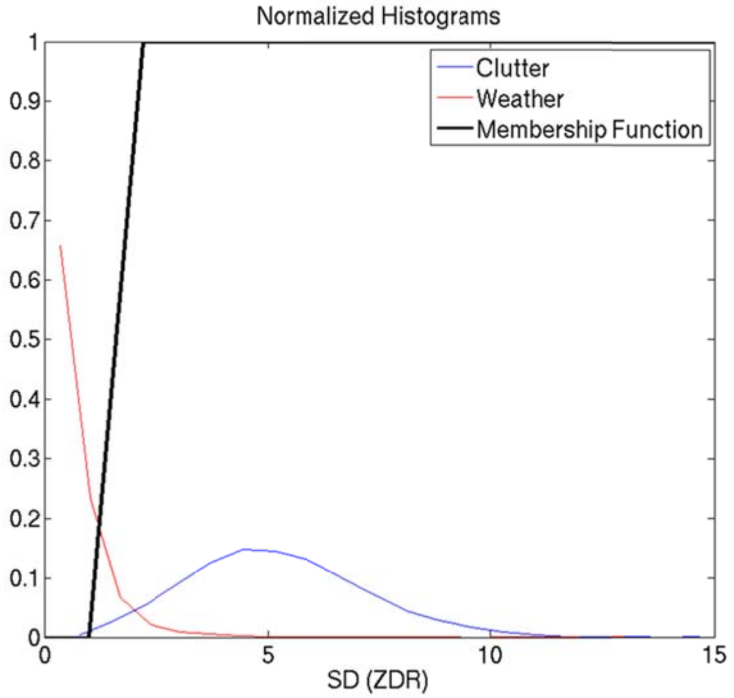

Figure 2 – SD ZDR Histograms of Weather and Clutter and Membership Function

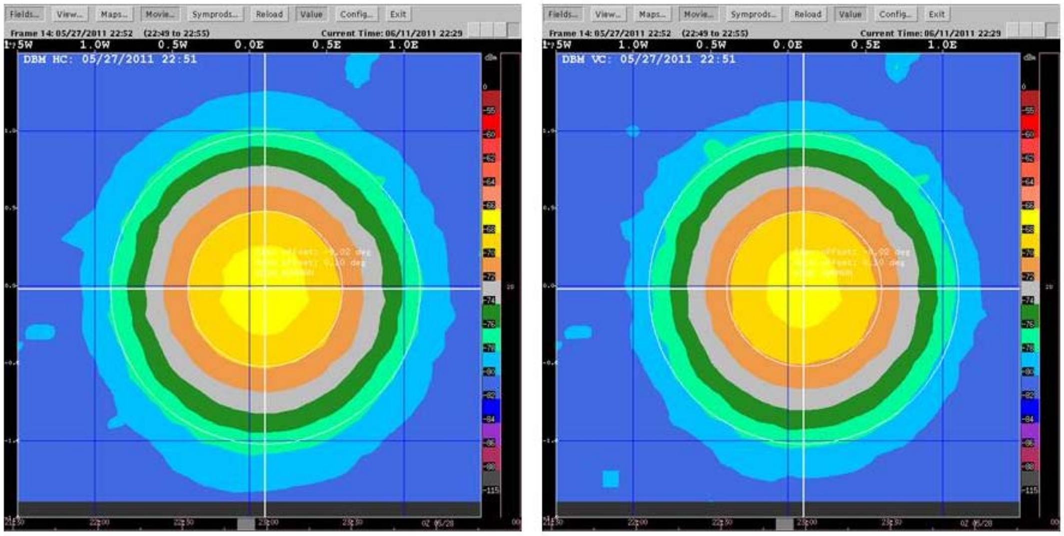

Figure 3 – H and V Solar Scans

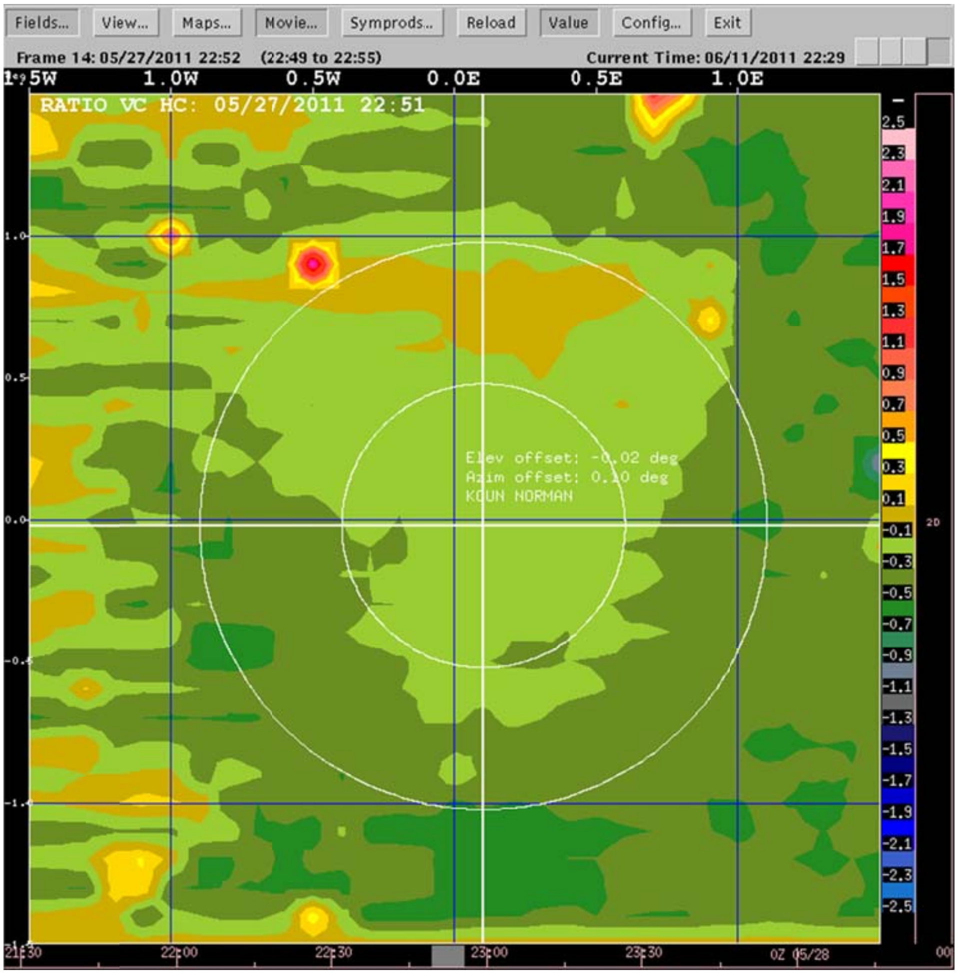

Figure 4 Difference in H and V Solar Scan Power

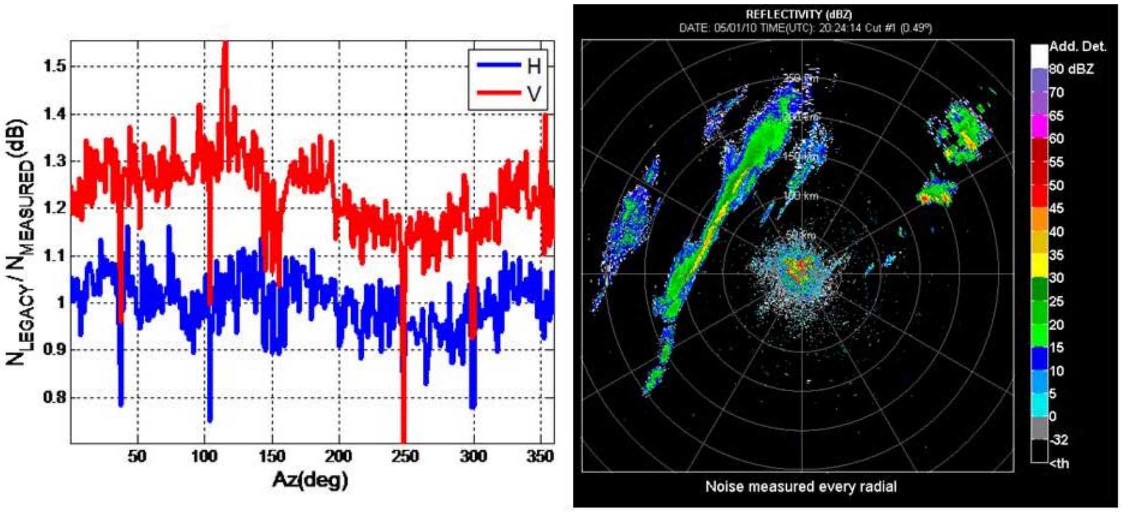

Figure 5 – Baseline Method vs. On-line estimate for noise

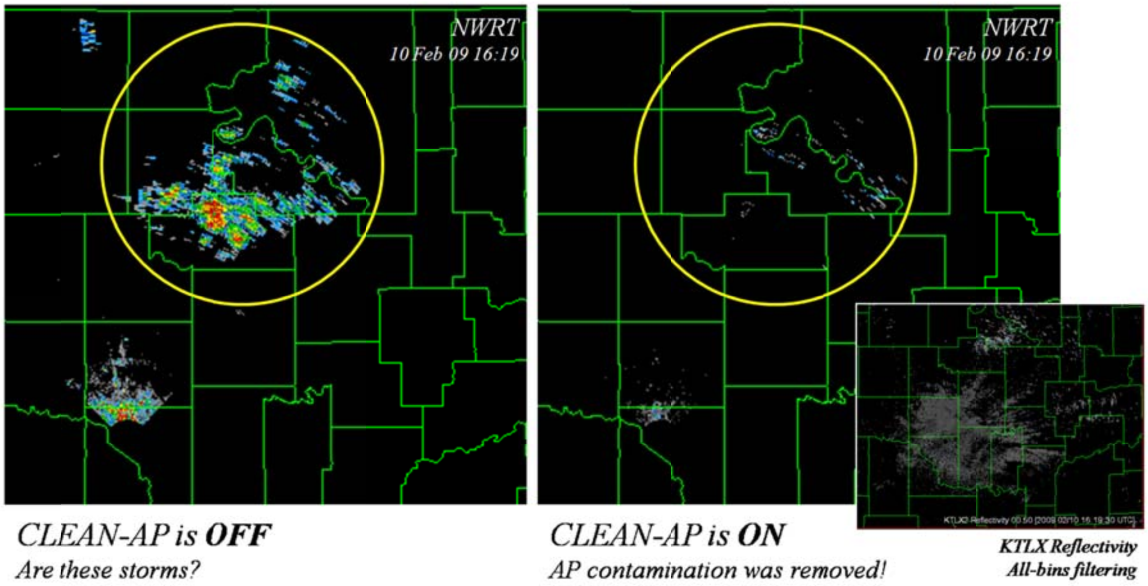

Figure 6 – CLEAN-AP Automatically Removing AP Clutter

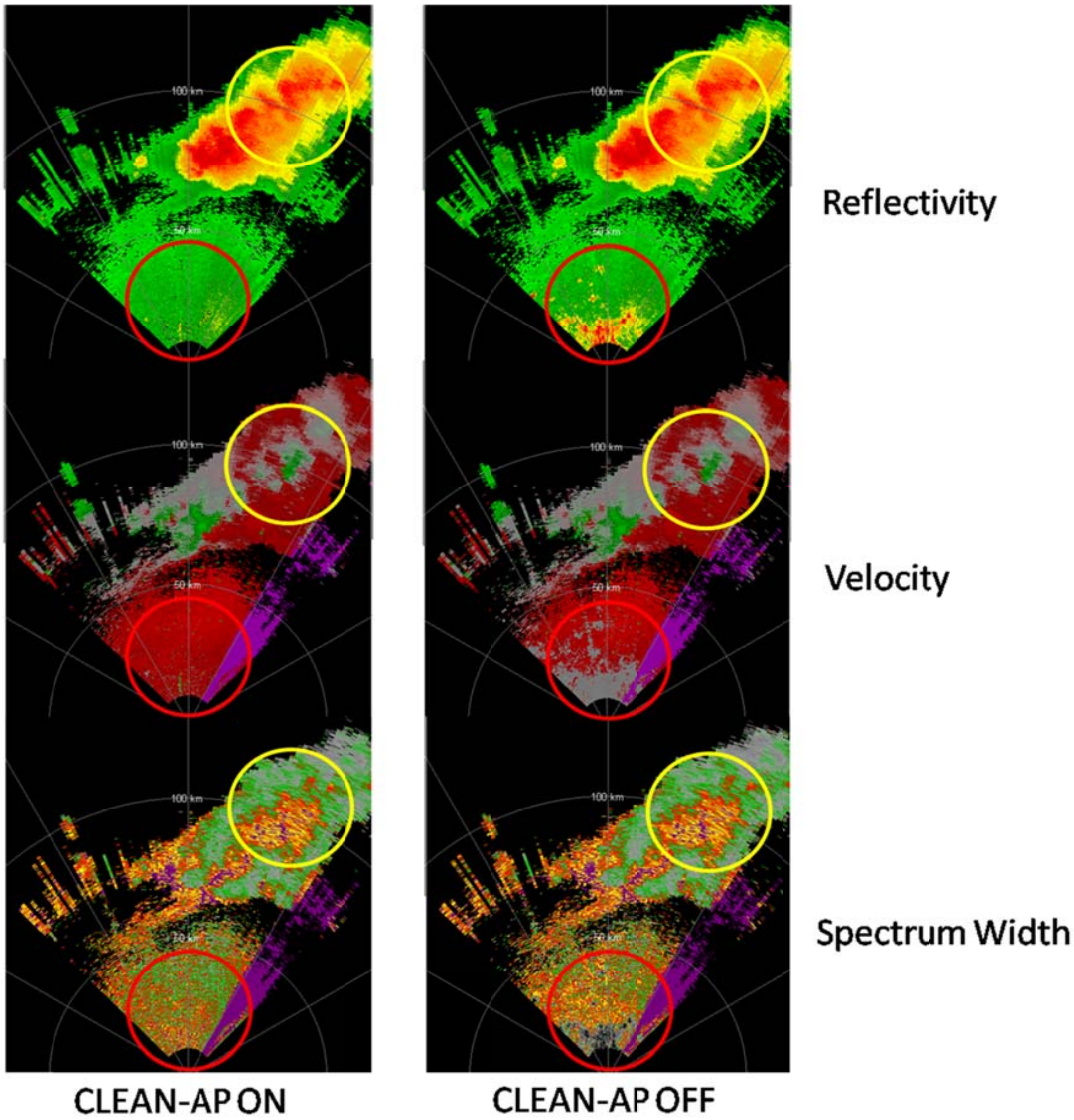

Figure 7 – CLEAN-AP Operating on the National Weather Radar Testbed

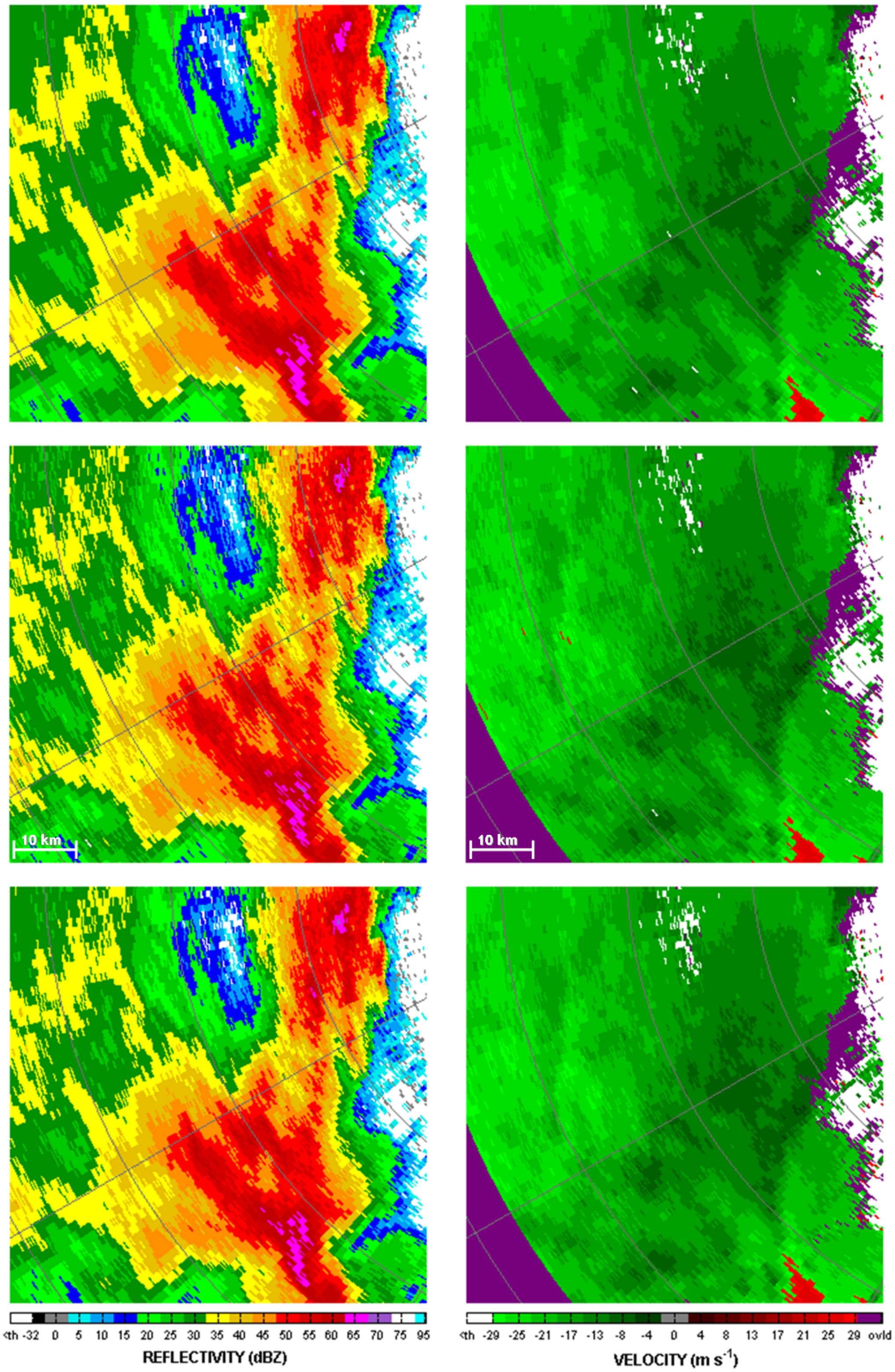

Figure 8 – Comparison of Matched Filtering and Two Oversampling and Whitening Methods