P5.3

AUTOMATIC CLUTTER MITIGATION IN THE WSR-88D, DESIGN, EVALUATION, AND IMPLEMENTATION

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1. INTRODUCTION

The WSR-88D Radar Operations Center (ROC), and the National Center for Atmospheric Research (NCAR), have developed an automated technique known as the Clutter Mitigation Decision (CMD) algorithm for identifying ground clutter. This new method is based on an algorithm that analyzes spectral and spatial characteristics of the radar return signal and produces a clutter contamination probability for each resolution cell (range bin) of the radar data array (Dixon et. al. 2005a,b, Hubbert et. al. 2008).

The algorithm features a new clutter identification parameter, the Clutter Phase Alignment (CPA, Hubbert et. al. 2009a). CPA is essentially a measure of the phase variability of the received time series samples for a given radar resolution volume. The algorithm also analyzes the radar reflectivity moment for two spatial characteristics. These are the Reflectivity Texture (TDBZ) and the Reflectivity SPIN change (Hubbert et. al. 2009b). Texture is a measure of the variability of the reflectivity field and SPIN is a measure of the number of times the reflectivity gradient changes sign along the radial (Steiner and Smith, 2002).

NCAR has developed both non-polarimetric and polarimetric versions of the CMD algorithm. The ROC implemented the non-polarimetric, Version 4.1, of the CMD algorithm delivered by NCAR in late 2007. The ROC team integrated CMD into the WSR-88D Baseline and completed engineering testing in the Winter of 2007 and early Spring of 2008. Software Beta testing began in the Spring of 2009 and CMD deployed with RDA software Build 11.0 in the Summer of 2009.

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This paper addresses details of the software design and integration, summarizes the engineering testing, and presents results of initial field deployment and evaluation.

2. CMD ALGORITHM DESIGN

The ROC has been actively working to improve both the efficacy and application management of clutter filtering in the WSR-88D system for some time (Ice et. al. 2007). NCAR developed the basic CMD algorithm as part of ROC sponsored data quality research. Early research primarily focused on a fuzzy logic approach using base moments, including spectrum width. A fuzzy logic based ground clutter recognition function, the Anomalous Propagation Detection Algorithm (APDA) was developed for the WSR-88D and hosted in the Radar Product Generator as the first installment of the Radar Echo Classifier (REC, C. Kessinger, et. al. 2004). REC-APDA products could be used by operators in manually managing the clutter filter application. In addition, the REC was incorporated in the Preprocessing Algorithm of the Precipitation Processing Subsystem (PPS) to mitigated ground clutter contamination in precipitation accumulation products. Some features of that algorithm, have been updated for use in CMD. Specifically, CMD uses the Reflectivity Texture (TDBZ), and Reflectivity gradient sign change count (SPIN) parameters, but the CMD algorithm employs them in an updated and more efficient manner.

The associated interest fields for these two feature fields are computed from fuzzy logic membership functions. CMD integrates them with the interest field from the CPA parameter to form the output probability of clutter for any given resolution volume. CPA is a new parameter (Hubbert et. al. 2009a), which computes the mean pulse-to-pulse phase stability of the time series I and Q data pairs using the following equation where I and Q are the individual in-phase and quadrature-phase components of each time series data pair for the resolution volume and m is the number of pairs.

$$CPA = \frac{\sqrt{\left(\sum_{i=0}^{m} I_i\right)^2 + \left(\sum_{i=0}^{m} Q_i\right)^2}}{\sum_{i=0}^{m}\sqrt{I_i^2 + Q_i^2}}$$

Fuzzy logic is based on the concept that there is not a simple binary conclusion to be obtained by examining key parameters of a process. For example, a simple threshold test is a binary process. If the magnitude of a given parameter is below some threshold value, it is discarded. If the magnitude exceeds some threshold value, then the parameter is passed on. The parameter is either used or not, yielding a binary result. Fuzzy logic examines features of a process, and through use of tailored functions, determines how "interesting" or relevant the feature is to a subsequent decision. In the case of CMD, these "Membership Functions" are linear. These functions use the Reflectivity Texture, SPIN change, and CPA as Feature Field inputs, and produce "Interest" values that range from 0 (not interesting) to 1, (completely interesting). These "Interest Fields" are then combined in a logic test to produce a probability that a particular radar resolution volume (bin) contains clutter. The probability ranges from 0 to 1.0 and the current algorithm declares that clutter is present if the probability exceeds 0.5.

TDBZ is a measure of the variability of Reflectivity over a spatial region. Clutter contaminated bins are generally more variable than bins containing pure weather returns. Figure 1 is an example of the TDBZ Membership Function which serves to illustrate the concept of converting a Feature Field to an Interest Field by using a linear transfer function.

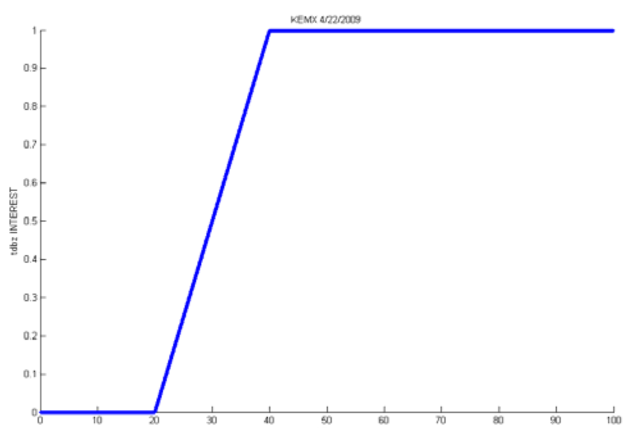

Figure 1 - TDBZ Membership Function, KEMX Data from April 22, 2009

This figure shows the range of TDBZ values from 0 to 100 and the subsequent TDBZ Interest values ranging from 0 to 1. Note the TDBZ Interest is 0 for values of TDBZ below 20 and the TDBZ Interest is 1 for values above 40. These membership function definition points were optimized by the NCAR science team, but can be changed for future releases via configuration files if needed.

Once the algorithm computes the Interest Fields for TDBZ, SPIN, and CPA, they are combined to form a probability of clutter contamination. TDBZ and SPIN interest are first examined and the maximum value of either of these is combined with the interest field for CPA using a weighted average approach to determine the probability of clutter. Then, as mentioned above, if the clutter probability value exceeds 0.5, a Clutter Flag is generated and the bin is identified as being clutter contaminated.

The CMD algorithm as delivered by NCAR also contains several data quality assurance features. The signals examined for the CMD parameters are censored with an adjustable threshold, there is a "Fill-In" feature that adds CMD clutter flags to isolated bins surrounded by clutter, and the algorithm includes a median filter to reduce false alarms, typically seen in zero isodop regions.

3. CMD ALGORITHM EVALUATION

NCAR performed extensive scientific testing of the CMD core processes and refined the algorithm performance over several years. Some of the results of that testing have been recently published (Hubbert et. al. 2009b). The NCAR evaluation consisted of extensive simulations as well as analysis of real radar data. Most of the actual radar data cases were collected in the Rocky Mountain Front Range areas near Denver and Boulder CO using both the Denver WSR-88D (KFTG) and the NCAR S-POL research radar. The KFTG data became available as part of the REFRACTT field program conducted in Colorado (http://www.eol.ucar.edu/projects/refractt).

A key performance parameter for any clutter detection algorithm is the detection probability as a function of the relative powers of the desired signal and the undesired clutter contamination. A Clutter to Signal Ratio (CSR) of 1/10 or -10 dB is desired to minimize bias due to mixing of the two types of return signals. Theoretical analysis of the case of overlaid echoes by the WSR-88D Operational Support Facility (OSF) in the early period of the NEXRAD program supports the value of -10 db CSR as a desirable target for any clutter detection scheme (Sirmans, 1990, Office of the Federal Coordinator for Meteorology, 2005). For example, in the case of a convective signal featuring a mean spectrum width of 4 m s^{-1} overlaid on clutter with a mean spectrum width of 0.5 m s^{-1}, the maximum velocity bias seen for a power ratio of 10 dB (signal to clutter) for velocities ranging over the Nyquist interval is less than 1 m s^{-1}, which is typically less than the error of the estimate.

NCAR reported on the performance of CMD's probability of detection (Hubbert et. al. 2009b). Figure 2 depicts the percentage of clutter contaminated gates identified by CMD versus the CSR. As seen in this figure, 50% of the clutter contaminated gates are identified by CMD for a CSR of around -8 dB. 100% of the gates are identified for CSR's above zero (clutter and signal powers equal) and about 10% of the clutter contaminated gates are identified when the CSR is around -15 dB. The present algorithm performance is acceptable based on operational radar data analysis.

The effects of clutter contamination of a desired signal are more severe for polarimetric parameters. Illingworth reports that the backscatter phase measurement is extremely sensitive to clutter contamination, with values of clutter amplitudes of 10 dB below signal adding 5 degrees of phase noise to the resultant signal (Meischner, 2004). He states that ground clutter with a Z value of 20 dB below that of the precipitation will render the value of the Backscatter Phase (PHIDP) “virtually useless”.

Fortunately, the algorithm performance can be improved by incorporation of polarimetric variables. Adding the standard deviation of Differential Reflectivity and the standard deviation of the Backscatter Phase parameters can improve the CMD detection performance by about 3 dB (Ellis 2009).

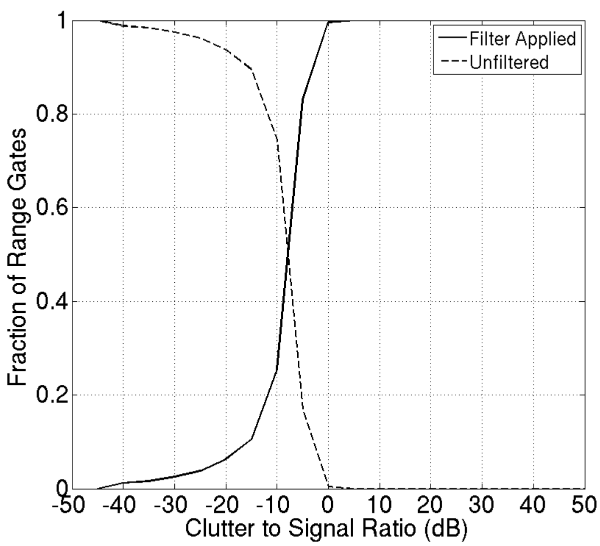

Figure 2 - CMD Clutter Detection, Single Polarization Case (Courtesy John Hubbert, NCAR)

4. CMD ALGORITHM IMPLEMENTATION

The ROC engineering design team worked closely with NCAR engineers and scientists to develop a practical approach for integrating CMD into the operational radar design. One of the basic problems was the variety of scanning strategies and radar signal waveforms employed by the WSR-88D. Another issue was the need for buffering time series data while the CMD clutter flags are generated, a potentially significant design issue because the first versions of the CMD algorithm employed a two dimensional “kernel” consisting of multiple radials and several range bins for computing the reflectivity texture and SPIN parameters. The engineering team and NCAR addressed this issue by redesigning the algorithm to use a one-dimensional kernel that only examines range bins in a single radial. NCAR testing showed that this simplified approach did not degrade algorithm performance.

The WSR-88D applies clutter filtering according to operator selected modes and application regions. Operational scans can apply different clutter filtering maps (or application schemes) to five segments of the various elevation scans (Chrisman and Ray, 2007). Several design decisions were aimed at reducing the impact to training and field operations. An early design decision was to retain the five segments of unique clutter filtering maps and not attempt to create a unique filtering approach for each elevation scan. The design team also decided to limit the initial production version of CMD to operations in the so-called “split cuts”. These scans, in the lowest two elevation segments, use a long PRT Surveillance scan followed by a short PRT Doppler scan at the same elevation. This approach takes advantage of a built-in feature of the RVP-8 signal processor. Due to the way it manages clutter filtering, the RVP-8 has the inherent capability of providing two data streams, providing both filtered and unfiltered reflectivity moments to the RCP-8 control processor.

The design team used this feature and integrated the CMD clutter flag generation algorithm into the Surveillance scan processing. During the long PRT Surveillance scan, CMD generates and sends the clutter flag array to the RCP-8 which hosts the RDA software. The RDA code then uses the clutter flag array to select either filtered or unfiltered data for subsequent transmission to the Radar Product Generator (RPG). At the same time, the ORDA code builds a clutter filter bypass map, using the baseline format, and downloads this map to the RVP8 for application to the Doppler scan per baseline operations. So, there are no changes to the Doppler scan software or scan strategies. This simple approach minimizes technical complexity, reduces processor load on the RVP-8, and does not require any special integration into advance range velocity mitigation techniques used in the Doppler scan such as phase coding.

The design approach used an unmodified version of the CMD clutter flag array to sort filtered versus unfiltered data for the Surveillance scans, then built the clutter flag array into a standard bypass map for use on the Doppler scan. For normal resolution processing, the filtering schemes would be the same for Surveillance and Doppler, with the filter application having a one degree by one kilometer resolution. However, for Super Resolution Mode, the two filtering schemes are different. The Surveillance data filtering is selected on a one-half degree by one quarter kilometer resolution, while the Doppler scan is filtered on the legacy one degree by one kilometer resolution. In addition, the Super Resolution radials are centered on one quarter kilometer increments (0.25, 0.75, 1.25 etc.) while normal resolution radials are centered on one half degree increments (0.5, 1.5, 2.5 etc.) This creates a need for mapping Super Resolution clutter flags into normal resolution maps.

Initially, the design team did not consider this to be a significant issue as the algorithm is tuned to provide increased probability of detection at the expense of an increase in false alarms. So the team reasoned that the clutter flags would be filled in and they did not expect significant differences in the Surveillance and Doppler scan filter applications for Super Resolution mode. This was certainly the case during the Engineering, Integration, and Systems level testing at the ROC and the test teams did not uncover any issues related to this approach prior to the Beta Test phase. An issue related to this approach did surface during Beta testing however, and this drove a design change as discussed below.

The design team also incorporated existing features related to clutter filter application. Operators can add clutter filter control zones to overlay on the CMD generated flags, using the same controls as before. Also, the CMD feature can be disabled, returning clutter filter control to the baseline approach. The implemented version includes a CMD status indication and use of CMD is documented in the system status messages. All bypass maps, whether generated by CMD or whether they are the static map are recorded in the Level 2 data stream and can be retrieved using software tools developed at the ROC.

Finally, the CMD algorithm was incorporated into the off-line system test software for use in generating static bypass maps. The CMD option is the default, but technicians can also select the legacy static map generation method which uses signal to noise ratio and clutter power removed as criteria for setting clutter flags.

5. CMD ENGINEERING TESTING

The ROC team conducted engineering testing between January and March of 2008. An interdisciplinary test team consisting of engineers and scientists from several ROC branches developed a test approach, collected test cases, and met each week to discuss results and adjust the testing process. The team examined results from new data sets collected from two Oklahoma radars: (KCRI, the ROC test bed), and KTLX, (the Oklahoma City WSR-88D). The team also replayed data sets to optimize some of the CMD variable parameters such as the SNR threshold and the span of the median filter. The test team also replayed archival cases, including data sets from the Denver and Albuquerque radars.

During the period from mid-February to mid-April 2008, the test team collected and analyzed several interesting cases, including two that featured small tornadoes in the Oklahoma City area. The following is a list of the test cases analyzed:

Live Data Collections:

- Feb 15 – 18: Rain, KCRI
- Feb 27: KCRI, CMD control tests, (clear air)
- Feb 29 – Mar 3: Cold front passage, OKC tornado warning, rain, KCRI CMD compare to KTLX map
- Mar 5 – KCRI: CMD control tests, clear air
- Mar 7 – 10 KCRI: weekend of clear air
- Mar 16 – 18 KCRI: frontal passage, rain
- Mar 31: KCRI and KTLX (Edmond OK, tornado)
- April 3 – 4: KCRI and KTLX (cold front, multiple outflow boundaries, AP)

Off-line and Replay Cases:

- Mar 14: Clutter map generation with multiple parameters
- Mar 19: more off-line map generation testing
- Replay Dec 11, 2007 rain event – 3 hr precipitation accumulation product analysis
- Replay April 24, 2007 KTLX AP Case
- Replay October 9, 2006 KFTG, Denver, CO snow event
- Replay April 9, 2007 KABX, Albuquerque NM, scattered showers in mountain clutter event

Early in the evaluation, the team focused on comparing operations using CMD with those from the baseline static bypass map. On March 3, 2008, a widespread rain event followed a cold front passage. The team was able to operate the KCRI test bed radar using the production version of CMD and compare results with those from the Oklahoma City WSR-88D (KTLX), which was using a static bypass map. Both radars were operating in VCP-12. Figure 3 is a sample of reflectivity and velocity for each radar for approximately the same time.

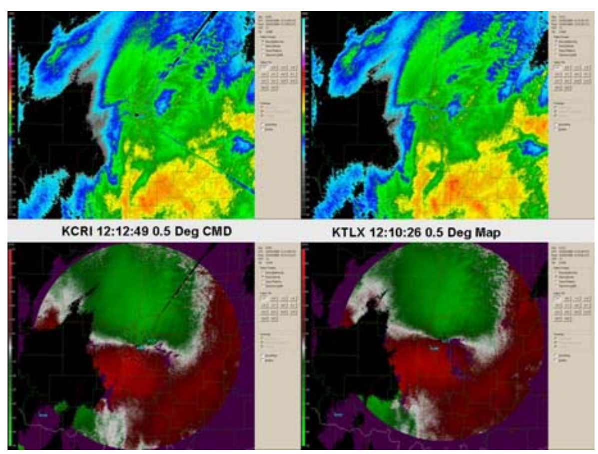

Figure 3 - CMD vs. Static Map KCRI – KTLX, March 3, 2008

The team did not note any significant issues with clutter contamination in the KCRI data using the CMD approach. The reflectivity and velocity fields for the two radars are remarkably similar. CMD did not exhibit any noticeable missed detections nor was it overly aggressive in applying filtering where it was not appropriate.

Engineers collected live radar data in clear air conditions to compare pure clutter identification and suppression with CMD compared to no clutter filtering and filtering for every bin. Figure 4 is a sample of this type of data showing reflectivity in three panels. The upper left panel is with no clutter suppression, the lower left is with CMD controlling the application of the filters and the lower right panel is for the case of "All Bins" where all radar resolution volume bins have clutter filtering applied.

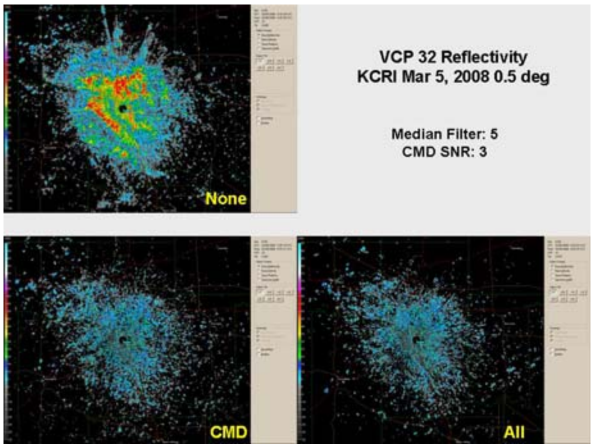

Figure 4 - Clear Air Ground Clutter Identification Test, Reflectivity March 5, 2008, KCRI

In Figure 4, the strong returns seen in the case of no clutter filtering are predominately ground clutter in the Oklahoma City area. The ridge associated with the South Canadian river valley is seen to the south west of the radar. The rest of the signals are from the usual clear air scattering targets seen at low altitudes. In the CMD and All Bins cases, the strong returns are removed. The CMD case retains more remaining meteorological return as fewer bins are filtered and thus unbiased by the clutter filters.

On March 31, 2008, a severe thunder storm moved through the Oklahoma City area. The test team captured data from the KCRI test bed radar, operating in Super Resolution with VCP12, and with clutter filtering under the control of the dynamic CMD feature. The next two figures present the view from KCRI and the Oklahoma City WSR-88D. Figure 5 compares the base reflectivity data for KCRI and KTLX. Note that KTLX was operating in VCP 12 with Normal Resolution and using a static bypass map at the time. The hook echo associated with the strong inflow is easily seen in both images. However, the detail from the Super Resolution display using one half degree radials and one quarter kilometer range bins is remarkable. There are no apparent issues with ground clutter contamination even though the storm is very close to both radars.

Figure 6 is the associated velocity data for this same time from both radars. While there are some areas of velocity aliasing in both sets of data, the main features in the images are similar. The test team did not observe any negative impacts to the data quality with use of the CMD dynamic clutter filter maps in the KCRI example.

During the evening of April 3, 2008, a squall line with embedded cells moved through central Oklahoma. The KTLX radar was operating with VCP 212 and using the static clutter map. This is an SZ2, phase coded, VCP and current operational guidance calls for operators to avoid use of the All Bins filtering approach as this can severely limit the SZ2 overlaid echo recovery algorithm. Because CMD should reduce the need for all bins filtering, it is particularly applicable when using SZ2 VCPs.

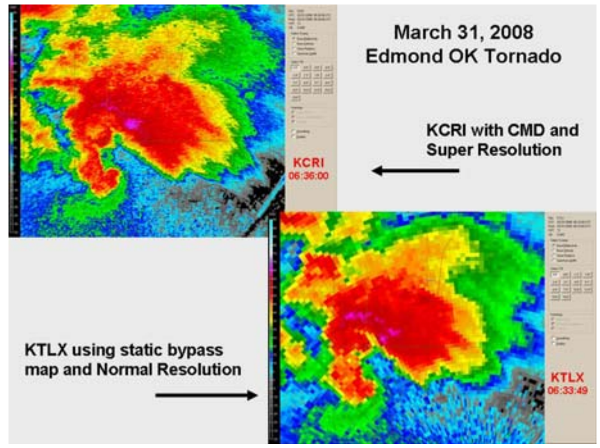

Figure 5 - Edmond OK Tornado, March 31, 2008, Reflectivity Data, KCRI and KTLX

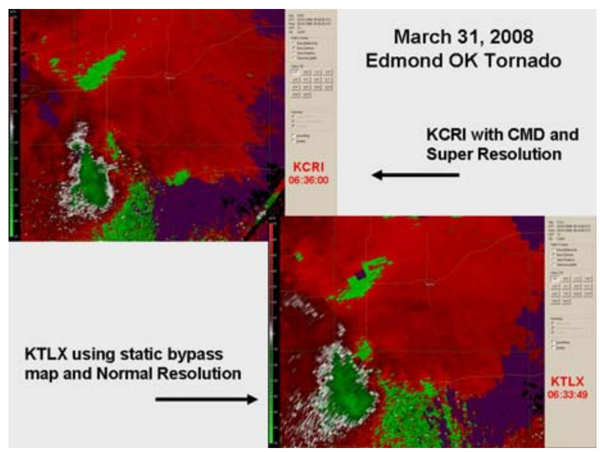

Figure 6 - Edmond OK Tornado, March 31, 2008, Velocity Data, KCRI and KTLX

KCRI was operating in VCP212 as well, but with the dynamic CMD clutter filter control active. At 23:51 (KCRI), and 23:52 (KTLX), the line had just passed the respective radar locations and anomalous propagation conditions were becoming established south east of the line. Figure 7 depicts reflectivity and velocity images from both radars with KCRI data on the left side of the figure. A fair amount of AP clutter is seen in the KTLX images, evident from the highly textured reflectivity and the large areas of zero velocity (white color) to the south east of the line. These features are absent in the KCRI data and an outflow boundary is clearly visible. Note that the AP clutter contamination obscures a significant portion of the outflow boundary as seen by the KTLX radar.

The test team was able to obtain time series data from both KCRI and KTLX due to a refractivity field experiment that had installed a time series recorder on KTLX. At about 00:11 on April 4, 2008, operators of the KTLX radar were forced to implement All Bins clutter filtering due to the severe AP clutter. The test team replayed this recorded time series data with the CMD dynamic map controlling the clutter filters. The results for reflectivity at the 0.5 degree elevation scan are shown in Figure 8.

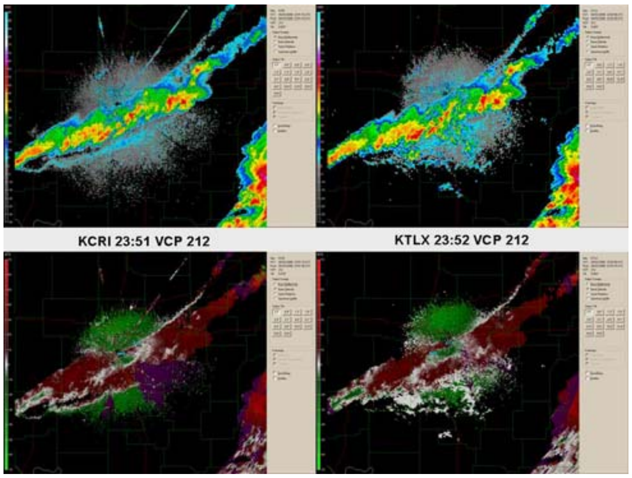

Figure 7 - Central Oklahoma Squall Line Passage, with AP Clutter, KCRI and KTLX, April 3, 2008

In this figure, large biases in the reflectivity are observed in the All Bins filtering case (white circle, upper left image. For the CMD case, some recovery of reflectivity values can be seen within the white circle in the lower right image.

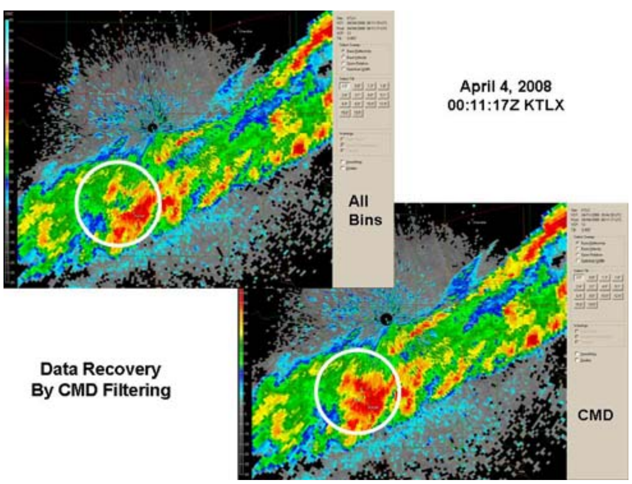

Figure 8 - CMD Reflectivity Recovery

The large reflectivity biases are due to near zero radial velocities in this region, probably associated with an area of vertical air motion within the cell. The velocity images for that area are shown in Figure 9, and repeat the white circles in Figure 8. Note that the CMD processed image shows the vertical air motion associated with the cell much more clearly. This is because fewer bins are being filtered, and these are unbiased as opposed to the biased velocity estimates from the All Bins filtered case.

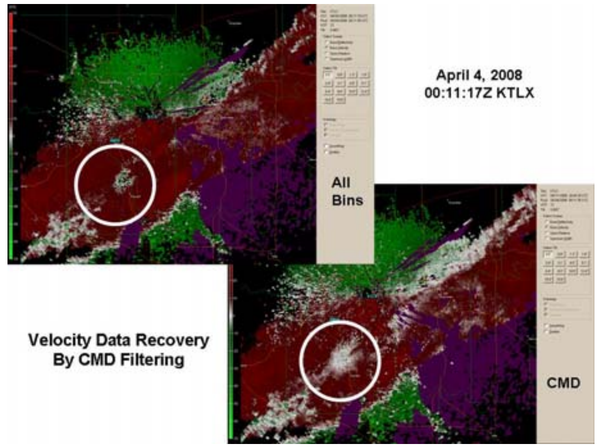

Figure 9 - Velocity Images, April 4, 2008, All Bins vs. CMD Control

The team replayed time series data from Denver CO (KFTG) and Albuquerque NM (KABX) to confirm CMD operational performance in mountain regions. Figure 10 is a sample of the replayed data for the KFTG radar in Denver for a snow storm that occurred in October of 2006. In this figure, the left panels show reflectivity and velocity processed with no clutter filtering. These panels show the strong clutter contamination from the front range of the Rocky Mountains with high reflectivity values and mostly zero velocities over a wide area. The right panels show the same data set, but with clutter filtering applied under dynamic CMD control. The bins of velocity and reflectivity data recovered are obvious when comparing the areas within the white ovals.

The team also processed time series data from Albuquerque (KABX). Figure 11 shows a similar comparison of that data for rain showers in the area and ground clutter from the Sandia Mountains. The clutter is removed by CMD applied filtering as seen in the panels on the right.

Another engineering test was to compare performance of the operational software with the prototype code maintained by NCAR to ensure the algorithm was correctly integrated. The engineering team reprocessed several cases using the ROC laboratory ORDA hardware and software and compared results with data processed by the NCAR team with their software. Results compared well and Figure 12 is a sample where the teams compared the CMD generated flags from both software baselines.

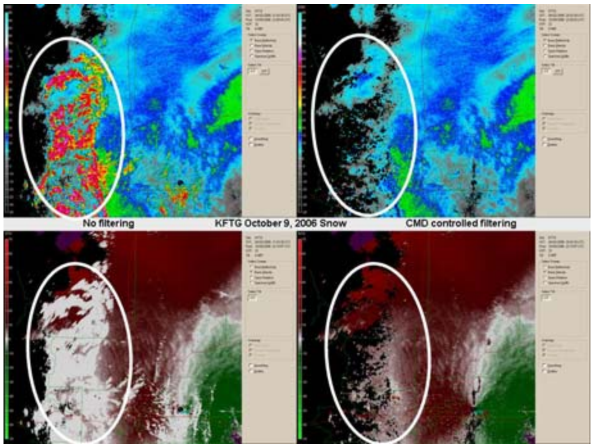

Figure 10 - KFTG Snow in Mountain Clutter

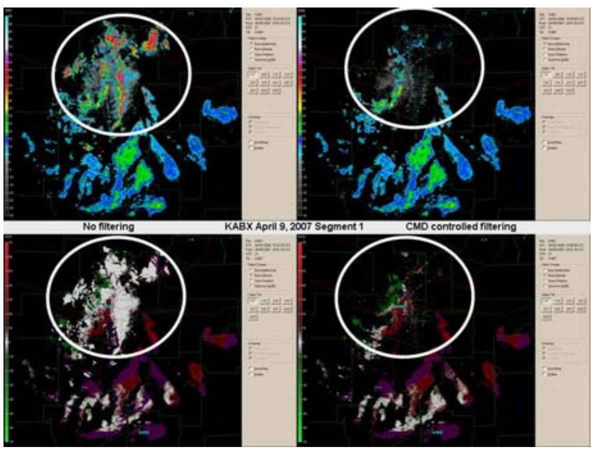

Figure 11 - Albuquerque NM Clutter Removed by Dynamic CMD Control

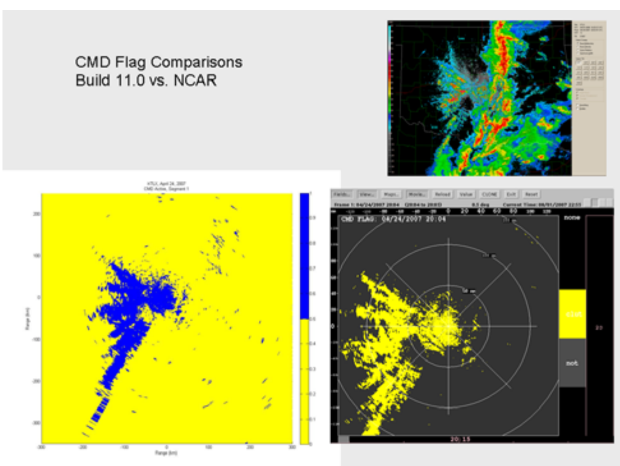

Figure 12 - NCAR and Build 11.0 CMD Flag Generation Comparison

The upper right image is the reflectivity from a severe AP case in central Oklahoma on April 4, 2007 with data from the KTLX radar. A squall line oriented north to south can be seen passing through the area. To the west, AP ground clutter is visible. The lower right image is the CMD clutter flag array from the Build 11.0 ORDA code and the lower right is an image provided by NCAR showing the clutter flag array from their baseline science code.

The engineering team performed quantitative analysis on the CMD clutter flags produced by NCAR and the ORDA software for the April 24, 2007 AP case. Figure 13 shows a MATLAB analysis of the difference between clutter flags generated by the ORDA software and the NCAR science code. The blue colors represent flags where the ROC's code produced a clutter flag but the NCAR code did not. There is a fair amount of difference, indicating the ORDA code is generating more flags. This is due in part to the CMD parameter settings chosen by the engineering team which result in fewer missed detections at the expense of a possibly higher false alarm rate. Other differences are due to operational implementation details related to beam indexing, super resolution and the final map building process in the ORDA. These differences did not point to any major errors in the code, and the team concluded the scientific algorithm was performing as expected in the ORDA production version..

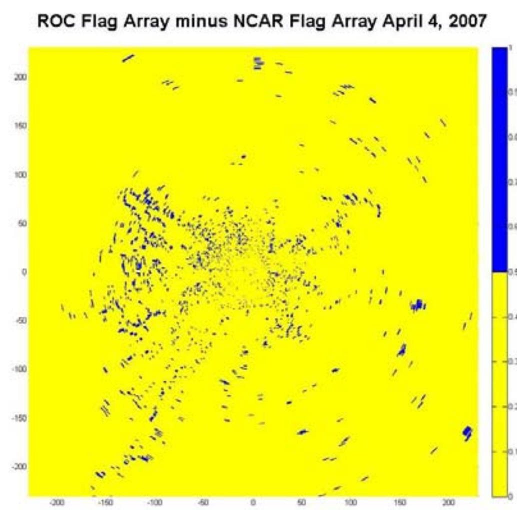

Figure 13 - Quantitative Flag Array Comparison - ROC versus NCAR Code

The team expected CMD to have a positive impact on precipitation accumulation products because clutter filtering is applied more judiciously, reducing reflectivity bias effects on the precipitation estimates. The team replayed 8 hours of time series data from the March 18, 2008 stratiform rain case using All Bins clutter filtering, static bypass map clutter filtering, and CMD controlled dynamic map filtering. The team processed

8 hours of Level 2 data on a laboratory RPG and produced 8-hour storm total precipitation accumulation products.

Figure 14 shows the large area display of the 8 hour storm total precipitation for the case of All Bins filtering (left panel) and CMD controlled filtering (right panel. The CMD processed case clearly shows more precipitation accumulated because there is less unnecessary clutter filtering producing negative biases in the reflectivity estimates. The negative bias in the accumulation is also evident in the zero isodop region of the All Bins case.

Figure 15 is a close up view of the area near the radar, which are the locations usually with the most ground clutter contamination.

Figure 15 shows a large region of the zero velocity isodop that exhibits significant negative bias in the precipitation estimate for the All Bins filtering case (left panel). The panel on the right shows the increased area of rainfall accumulation, with the zero isodop filled in. There are also regions of higher accumulation over a large portion of the display, indicating that the All Bins case resulted in significant underestimates of rain rates.

There are also some noticeable bright spots near the radar, mostly to the north and west. These are likely to be areas where CMD algorithm occasionally exhibited missed detections. These could be caused by ground vehicle traffic which can reduce the value of the CPA parameter, lowering the probability of clutter detection by CMD. These do not significantly impact rainfall accumulations.

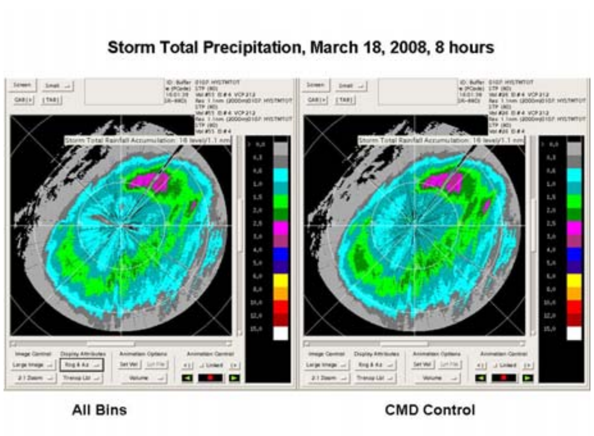

Figure 14 - Precipitation Accumulation, 8 hours, March 18, 2008, All Bins vs. CMD

The team then analyzed the performance quantitatively. Figure 16 is one sample of the analysis, a range dependent comparison of the reported accumulation for the All Bins and CMD controlled modes. The CMD mode produced higher average accumulations at ranges out to nearly 180 km, with significantly higher accumulations near the radar out to approximately 70 km.

The precipitation accumulation analysis was the final stage in the engineering test phase and the test team briefed the results to the ROC Data Quality Team on May 2, 2008. The Data Quality Team accepted the results and recommended CMD for use in Build 11.0. After various other management briefings, CMD was approved as part of the Build 11.0 System and Operations Tests. These tests were successful and Build 11.0 featuring CMD began Beta Testing in the Spring of 2009.

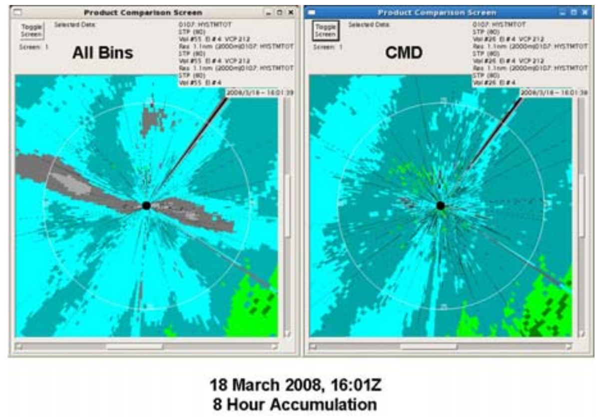

Figure 15 - Precipitation Accumulation Near the Radar, All Bins vs. CMD Control

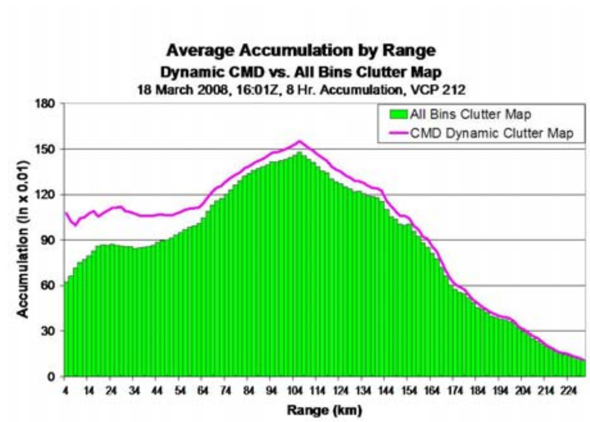

Figure 16 - Range Dependent Rainfall Average Accumulation, CMD vs. All Bins

6. BUILD 11.0 BETA TESTING

The ROC deployed Build 11.0 to several sites in the Spring of 2009. The KEMX radar at Tucson AZ was included in the Beta Test and the operations staff was quite helpful in monitoring CMD performance in their challenging mountain clutter environment. Site personnel quickly noted that under CMD clutter filter control, the data exhibited a few missed detections in a couple of mountain areas. These missed detections were manifested by very High reflectivity values in small areas. The reflectivity values were of a magnitude usually associated with strong ground clutter and resulted in large overestimates of precipitation in these small regions.

The ROC hotline and the Beta Test team issued a Request for Technical Information (RTI) which is the formal means for requesting technical assistance on field issues. Along with the RTI was a set of time series data the Beta Test team collected at KEMX. The KEMX site personnel also provided time series data sets in support of the ROC test team. The CMD engineering team used this data to understand the behavior of CMD in this mountain clutter environment.

Figure 17 illustrates the issue with the KEMX missed detections. It shows reflectivity images of a particular region to the north west of the radar. The two images are from the Surveillance Scan and the immediately following Doppler scan, both at 0.5 degrees. As part of the Super Resolution upgrade in Build 10.0, the reflectivity data from the Doppler scan of the split cuts is made available to the RPG.

The upper left panel is the Surveillance reflectivity and several bright spots of reflectivity are evident. These are characteristic of un-filtered ground clutter. The CMD algorithm, for this Super Resolution mode, was not identifying these bins as being clutter contaminated.

The engineering team immediately noticed that these bins were being filtered by the CMD and ORDA generated bypass map used on the Doppler scan. Note that in the lower right panel, the bright spots are eliminated. Based on the design, the Surveillance scan is filtered on a one half degree by one quarter kilometer resolution, the resolution of the CMD clutter flags coming from the RVP-8 for the Super Resolution mode. For the Doppler scan, the Super Resolution CMD flag array is translated into a normal resolution clutter bypass map that is compatible with the normal Clutter Filter Control (CFC) product. This map is used to control filtering for the Doppler Scan and then sent to the RPG for recording in the Level 2 data stream and subsequently provided as a CFC product.

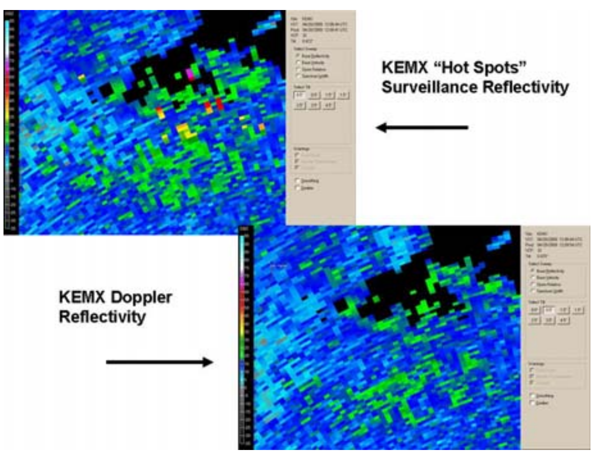

Figure 17 - Bright Spots in KEMX Surveillance Reflectivity Data

In the initial design then, there could be differences in the clutter filter control maps for Surveillance and Doppler scans. This did not cause any issues during Engineering, System, and Operations testing at the ROC. However, the unique terrain near Tucson caused CMD to have a higher probability of missed detections. These missed areas were filled in by the map translation process from Surveillance to Doppler, resulting in the spots being eliminated in the Doppler reflectivity.

This phenomena formed the basis for a design change to address the problem. For Build 11.1, deployed in the Summer of 2009, the filtered vs. unfiltered selection process was changed for the Surveillance scan. In the updated design, the normal resolution (one degree by one kilometer) map is used for both Surveillance and Doppler scans. The somewhat larger filter application area addresses the occasional missed detections seen in some types of terrain. It does result in slightly more Surveillance reflectivity bins being filtered when compared to the original design, but the probability of a clutter contaminated bin being missed is greatly reduced.

Although the decision was made to deploy this change to address the missed detections, engineers at the ROC and NCAR continued to analyze data to determine the cause of the CMD missed detections for these certain terrain areas. Further investigation identified that this phenomena occurred more often than previously thought. Missed detections were identified in Beta Test phase data from Sacramento CA, and were also seen in reprocessed data from Albuquerque NM. Only one or two missed bins were seen in the Denver CO data, explaining why this had not been identified earlier in the development.

Engineers used several MATLAB routines developed at the ROC to analyze the spectral characteristics of the time series data from the offending bins. Figure 18 shows the expected spectrum from a ground clutter contaminated bin lying on an azimuth of 344.5 degrees and at a range of 57.5 km from the radar. The spectrum was processed using 64 samples centered on this location. Note that the spectral coefficients are centered on zero velocity, have a reasonably narrow spectrum width and exhibit an apparent Gaussian shape with a single peak, or mode.

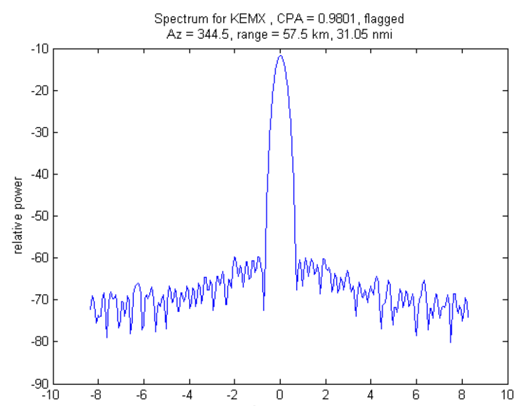

Figure 18 - Spectrum of a Normal Clutter Target

In this example, the calculated value of CPA is high (0.9601) and the CMD flag array data confirms that this bin was correctly identified as clutter. Figure 19 shows the receiver voltage amplitude of the samples in the bin with the first sample on the left and the 64th sample on the right. Note that the amplitude plot has a fairly smooth, almost sinusoidal appearance, absent of abrupt changes in direction. This is characteristic of a coherent target being scanned by the radar. The corresponding phase plot would also exhibit a smooth appearance.

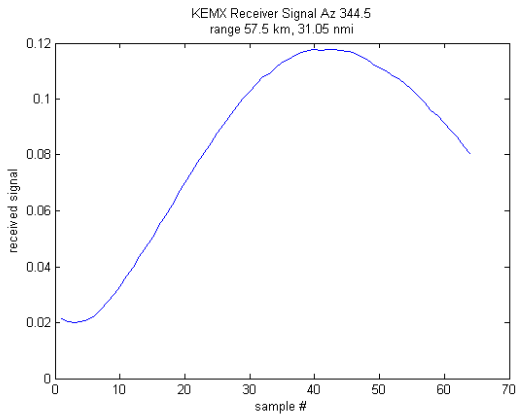

Figure 19 - Receiver Voltage Magnitudes for Sample Set, Normal Clutter Target

Figure 20 is the spectrum of one of the bins missed by the CMD algorithm. This is at an azimuth of 345.25 degrees and is bin number 238 (59.5 km). Note the bimodal spectrum near zero and the high side lobes over the entire Nyquist interval. The CPA for this bin is quite low (0.1299), indicating a noise like signal. CMD did not flag this bin as clutter.

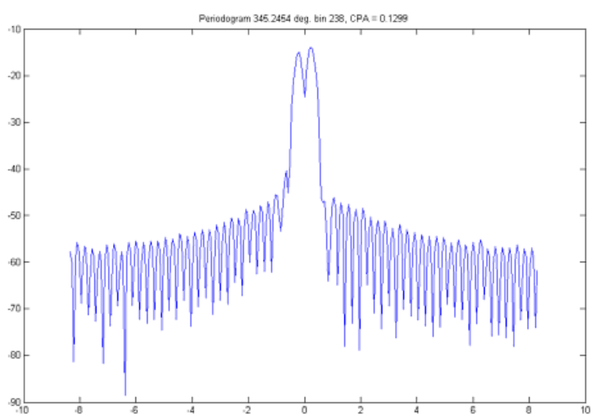

Figure 20 - Spectrum of "Odd" Clutter Target

The team looked closely at the receiver time series for this bin, examining both the magnitude and phase of the received samples as the antenna beam moved across the target. Figure 21 shows the magnitude (upper plot) and the phase (lower plot) for this set of time series samples. The receiver voltage magnitude exhibits an abrupt change in slope, and there are two distinctly different phase values with a rapid transition near the middle of the sample set. This appears to be caused by two point targets in the radar resolution volume. For the first part of the sample set, one target's phase, which represents its mean distance from the radar in terms of wavelength, dominates the signal. Then a transition occurs, and the second target's phase dominates for the latter part of the sample set. The phase change is nearly 180 degrees (about 3 radians). Since CPA is calculated over the entire set, and is a measure of phase stability, CPA is quite low for this sample set.

This data may prove useful for improving the CPA computational algorithm, and engineers on the project have discussed various ideas. While this data is interesting and useful for future enhancements to CMD, further analysis is not needed for the current software. The design update featuring use of the normal resolution maps addresses the issue of an occasional missed detection. This phenomena has not been seen to any great extent with Build 11.1 operations. The ROC teams conclude that the design update adequately handles these isolated missed detections and this is not an operational concern.

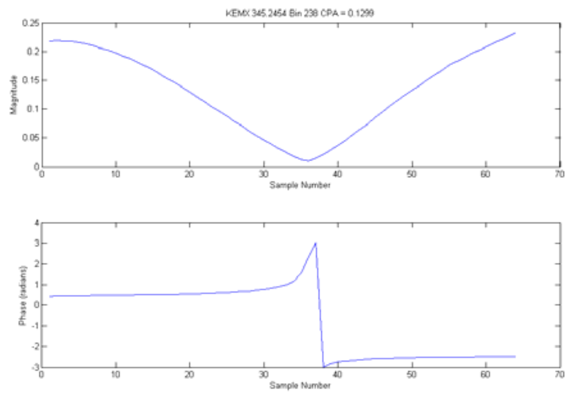

Figure 21 - Magnitude and Phase Plots, Low Coherency Clutter Target

7. BUILD 11.1 DEPLOYMENT MONITORING

The ROC continues to monitor CMD performance as Build 11.1 deploys to all WSR-88D systems. The Operations Branch Hotline, Engineering, and Applications Branch scientists and engineers analyze a sampling of cases each week. Interesting cases related to CMD performance are discussed each week in the interdisciplinary Data Quality Team meeting. These meetings are attended by NSSL, University of Oklahoma, and ROC team members. To date, all questions from the field have been answered satisfactorily and no new design issues have been noted. One interesting example of CMD utility is from the Topeka KS radar (KTWX) that occurred on August 10, 2009. A fairly large complex of storms passed through the area, and a wide area of AP began to set up to the north and north west of the radar. The CMD dynamic clutter filter control mode was in effect. CMD controlled clutter filtering was identifying and filtering AP ground clutter to the north as a boundary moved through.

Figure 22 is a sample of reflectivity, velocity, and storm relative motion velocity for the time 20:13:54 UTC on August 10, 2009. Even though it is in a region of AP clutter under automatic filter control, the boundary is clearly evident. In this case, operators of KTWX did not have to manage clutter filtering schemes during weather operations as the CMD dynamic map was handling the AP with no apparent degradation of radar data.

8. SUMMARY

This paper addressed the implementation, evaluation, and extensive testing programs for the CMD automatic clutter identification algorithm. CMD was successfully deployed in 2009 in RDA software Build 11.1 after over a year and a half of test and evaluation. CMD has been shown to be an effective way to automatically manage the application of ground clutter filters for the lower elevation scans of the WSR-88D. This experience reinforces the relevance of a comprehensive test program, including engineering, systems, operations and beta test phases. In this instance, beta testing identified a need for a design change that was undetected in earlier development and test phases. The complexity of modern software systems drives a need for a multi-layered test approach and the WSR-88D system has benefited from the interdisciplinary process in place at the ROC.

CMD can be counted as a success, but its performance can be improved via algorithm tuning and the integration of polarimetric variables. The ROC, NSSL, and NCAR teams plan to enhance CMD for a future release after the WSR-88D Polarimetric Technology upgrade is deployed.

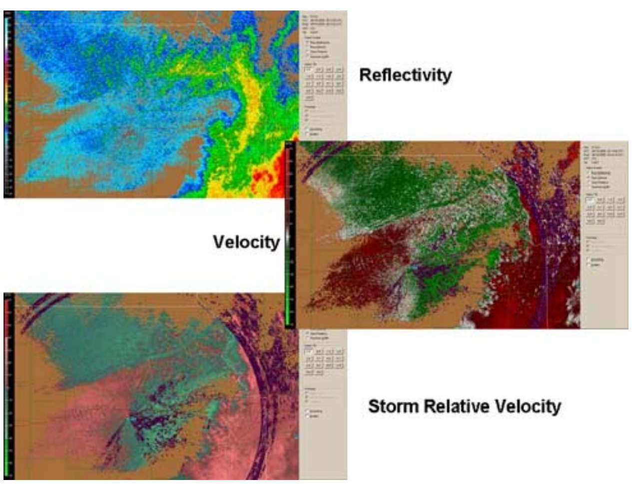

Figure 22 - Boundary Moving through an AP Clutter Area, Topeka KS, August 10, 2009.

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