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## 1. INTRODUCTION

The WSR-88D Radar Operations Center (ROC), the National Center for Atmospheric Research (NCAR), and the National Severe Storms Laboratory (NSSL) are investigating performance enhancements for the WSR-88D clutter filters and options for improving efficiency of the clutter filtering application. Areas of investigation include fine tuning the performance of the Gaussian Model Adaptive Processing (GMAP) filter used in the Open Radar Data Acquisition (ORDA) system and exploring better methods to adapt the filters to the combined clutter and weather environment. Plans include integrating into the WSR-88D an automated clutter filter control application developed at NCAR, and implementing a staggered Pulse Repetition Time (PRT) capability which will eventually include a new clutter filtering method developed at NSSL.

This paper presents current plans, status, and some preliminary design considerations for clutter filtering and application enhancements.

## 2. INHERENT EFFECTS OF CLUTTER FILTERING

While clutter filtering is often necessary when meteorological signals are contaminated with undesired components, such as ground reflections, the application of filters usually affects the desired signal quality. With the advent of faster processors and the development of sophisticated signal processing techniques, filtering methods now available can minimize these effects.

The most common effects of clutter filtering include biases in all the usual measurements of reflectivity, velocity and spectrum width. Biases in reflectivity directly influence rain rate estimation, most often resulting in total precipitation underestimation. The filtering process also introduces noise into the signal, increasing variance of the estimate. Researchers and system developers attempt to minimize the adverse effects of clutter filtering through continuous improvement in filter design and by providing tools to assist radar operators judiciously apply clutter filtering. As will be seen in the following sections, even the most sophisticated clutter filters available will produce adverse effects on radar data and filters should always be used only when and where needed.

The next sections discuss the original WSR-88D filters and the new Open RDA filters, followed by some examples of how weather data can be affected by filtering.

## 3. LEGACY WSR-88D CLUTTER FILTERING DESIGN

The first generation WSR-88 systems, sometimes now referred to as "legacy", incorporated two classes of time-domain clutter filters. Both a 5 Pole Elliptic Infinite Impulse Response (IIR) filter and a simple two pulse canceller filter were included. The IIR filter was used for all modes of the radar except for cases where the small number of surveillance pulses from the Batch mode were processed. In the latter case, the two pulse canceller was employed for clutter filtering.

At the time of the WSR-88D development and deployment, signal processors were simply not powerful enough to incorporate frequency domain techniques (also known as spectral processing). The legacy filter was essentially a high pass system, incorporating a time domain design that eliminated signal components associated with Doppler velocities below a specified value. This value, known as the pass band edge velocity ( $V_P$ ) was dependent on operator selection and radar operating modes. Also, because of the time

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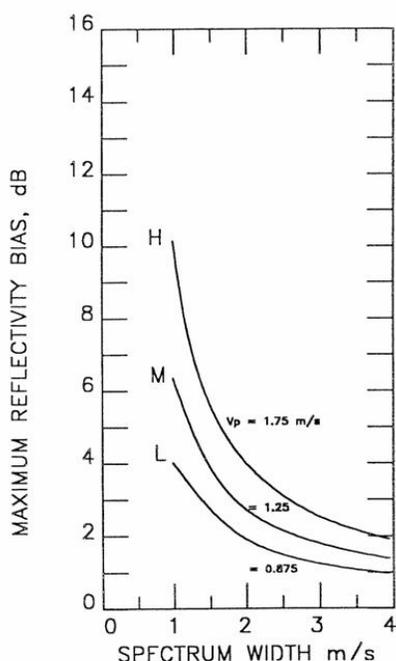
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domain nature of the filter, it had several undesirable characteristics. The filter processing loop needed to be initialized when system operational modes changed (e.g. with a change in PRT) and it exhibited problematic transient characteristics (e.g. data smearing in areas with high reflectivity gradients). A full description of the legacy WSR-88D filter is documented in an Operational Support Facility (OSF) report (Sirmans, 1992) available from the ROC.

An especially undesirable characteristic of the legacy IIR filter was that it introduced significant levels of negative bias in the reflectivity estimates which resulted in severe underestimation. Figure 1, adapted from the OSF report, shows the magnitude of the bias for the surveillance mode as a function of signal spectrum width and the amount of suppression selected by the operator. Increasing selected suppression level results in a larger pass band edge velocity.

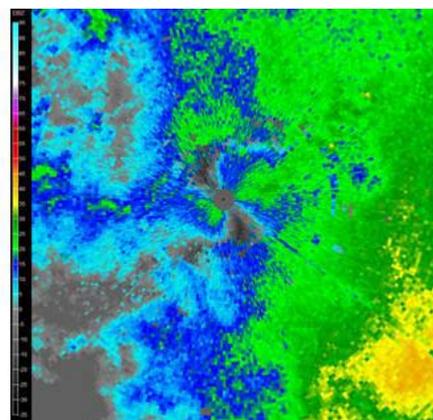


**Figure 1 – Legacy Clutter Filter Reflectivity Bias**

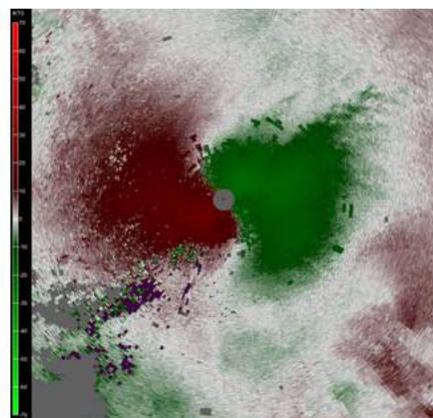
The curves in Figure 1 represent the bias of the legacy filter for the three operator selected levels of suppression as indicated in the labels on the left of the graph (Low-L, Medium-M, High-H). The bias is for a zero mean velocity weather signal calculated as a function of signal spectrum width. As seen, for the high suppression setting, bias exceeds 2 dB for signals with spectrum widths less than about 4.0 m/s. The bias can exceed 10 dB for very narrow width signals.

Figure 2 is an example of the bias induced in reflectivity estimates by the legacy clutter filter (a) along with the corresponding velocity image (b). This data is from a Great Plains region radar system showing the bias effects on a stratiform rain case (2.4 degree

elevation) using Volume Coverage Pattern (VCP) number 12. Note the loss of reflectivity data in (a) for regions corresponding to the zero isodop as seen in (b). This is seen in the dark region centered on the radar with the characteristic "butterfly wing" shape that continues outward following the corresponding zero velocity region.



(a) Reflectivity 2.4 °



(b) Velocity 2.4 °

**Figure 2 - Legacy Filtered Data**

#### 4. OPEN RDA CLUTTER FILTERING DESIGN

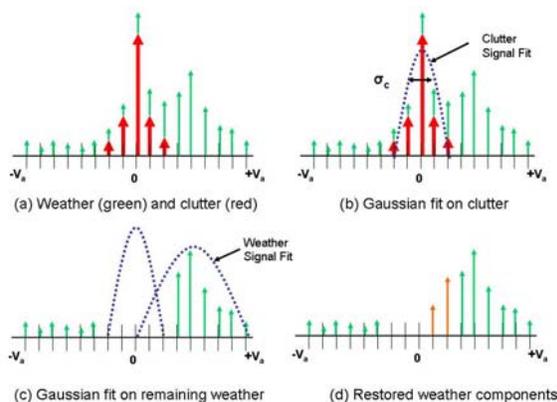
The ORDA upgrade, which includes a new digital receiver, signal processor, and control computer, makes real-time frequency spectral processing techniques possible. The ORDA uses a particular type of spectral clutter filter, the GMAP filter developed by SIGMET (Passarelli and Siggia, 2004). This filter has been validated by the ROC for use in the ORDA (Ice et. al, 2004, 2005). Early experiences with the GMAP filter and ORDA clutter filtering and censoring indicate improved performance over the legacy filter (Chrisman and Ray, 2005). Figure 3 depicts the basic concepts of the GMAP clutter filter.

This example is for a spectrum obtained with 17 time series samples. This produces a symmetric set of

spectral coefficients about the zero frequency/velocity point and approximates the WSR-88D Surveillance mode for typical volume coverage patterns.

Panel (a) shows the basic combined weather and clutter spectrum. Components associated with clutter are indicated by the red arrows while components associated with weather are represented by the green arrows. The clutter components are centered about zero, as expected. The weather components have a positive mean value at about the halfway point in the Nyquist interval between zero velocity and the positive unambiguous velocity ( $+V_a$ ). In the clutter region, the clutter and weather signal component powers add, indicated by the weather components sitting atop the clutter components. If left unfiltered, the moment estimates made from this spectrum would have a large positive bias in reflectivity and a bias towards zero for the velocity estimate. Also, the spectrum width estimate would exhibit a large positive bias.

Panel (b) depicts the first step in the GMAP process. Using a supplied clutter spectrum width value, the algorithm fits a Gaussian curve to the coefficients centered about the zero velocity point. The amplitude of the curve is a function of the power contributed by the clutter and weather coefficients. The standard deviation of the fitted Gaussian is determined by the supplied clutter spectrum width seed value ( $\sigma_c$ ). The algorithm will remove all components contained within this curve that are above the system noise level. Note that as the value of  $\sigma_c$  increases, more coefficients will be removed by GMAP. For this example, all five combined clutter/weather components fall within the fitted curve.



**Figure 3 - GMAP Filtering Concept**

Panel (c) shows the elements of the weather signal spectrum remaining after the components associated with clutter have been removed. Note that this point in the process roughly corresponds to the legacy filtering process. At this point the legacy filtering process would be finished and the moments would be estimated from the time domain signals associated with the significantly altered spectrum. However, GMAP continues on with an attempt to rebuild the lost weather spectrum components. The algorithm iteratively fits a Gaussian curve using the remaining spectral components,

represented by the dashed blue line in panel (c). (Note: the clutter Gaussian fit is also shown for reference). The resulting Gaussian function fit to the weather allows GMAP to compute the magnitudes and spectral locations of the restored weather components. Panel (d) shows that, for this case, two components are restored to the spectrum.

Note that the restored spectrum does not exactly replicate the original elements associated with the weather signal. Therefore, GMAP filtering also introduces some biases into the estimates. However, GMAP should have less of a detrimental effect on the moment estimates than the legacy filters. The spectrum in (d) will produce a more accurate estimate than the spectrum in (c), which would be closer to the legacy IIR filter performance.

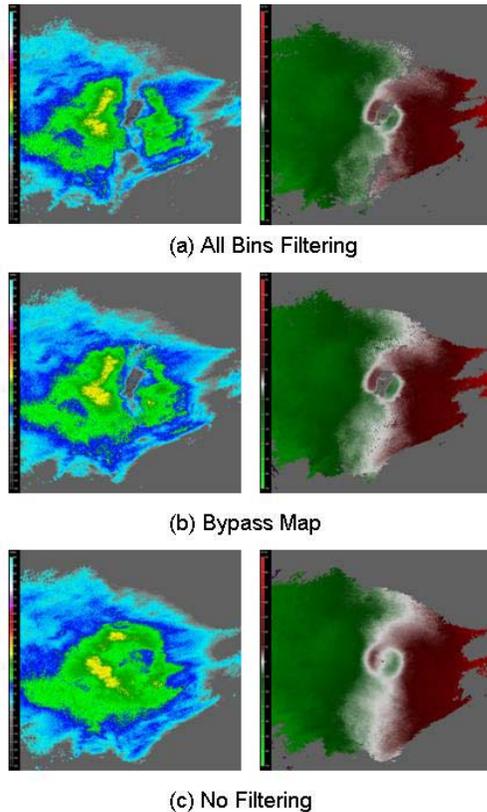
The GMAP process is limited to a clutter suppression level of around 55 dB, depending on the level of phase noise within a particular radar. This more than exceeds WSR-88D requirements (Ice et. al., 2005), but does not remove some very strong clutter targets which can reach 80 dBz. The ORDA incorporates additional clutter residue censoring in a manner similar to that of the legacy system (Free and Patel, 2005). The system adjusts the signal threshold levels upwards when the amount of removed clutter power exceeds a specified level. The result is, for areas of very strong clutter, all of the power will be removed by the censoring action of the system. The ORDA has fewer of these cases because GMAP rebuilds a portion of the weather signal.

## 5. ANALYSIS OF GMAP PERFORMANCE

The WSR-88D Data Quality Team is an interdisciplinary group with members from the ROC, the NWS Warning Decision Training Branch, and NSSL. This group continuously monitors ORDA data quality. The team examined products from nearly every ORDA system as the retrofits took place. Early results with the ORDA have proven to be generally acceptable, but with a few areas for improvement noted. This initial analysis has resulted in two near-term enhancements that will be incorporated in ORDA Software Build 9.0 in mid 2007. These are discussed in the next section.

Very early in the ORDA deployment, operators at a site in the southeast noted significant losses in reflectivity along the zero isodop for a mild stratiform rain case. The site reported this to the WSR-88D Hotline and on-duty meteorologists assisted the site with clutter filter management. The Hotline representatives identified the use of the "All-bins" clutter filtering option as a contributing cause of the excessive losses. In the All-bins mode, clutter filtering is applied to every moment estimate. The Hotline instructed the site to invoke their currently available bypass map instead of using the All-bins mode. The site did so, resulting in recovery of additional reflectivity estimates. The site also collected data for a volume scan with no filtering applied.

Figure 4 shows the reflectivity and velocity images for the three clutter filtering options: all-bins filtering, bypass map filtering, and no filtering.



**Figure 4 - GMAP Filtering on Stratiform Rain**

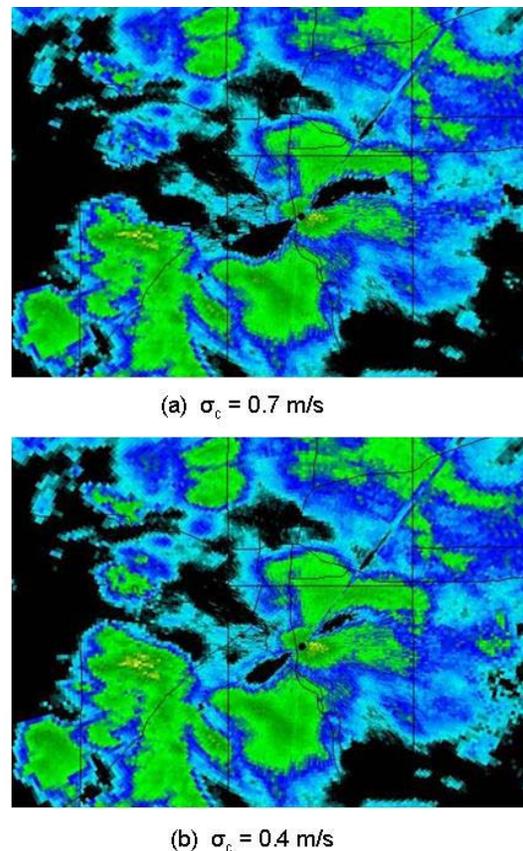
In Figure 4, reflectivity is on the left and the corresponding velocity is on the right. Note that in the all-bins mode (a), there is a fairly large area of reflectivity data loss along a north south line which intersects the radar location. When the site switched to the bypass map (b), a large portion of this data loss was restored. Finally in (c) the site turned off all clutter filtering resulting in restoration of most of the weather signal. This data set is for the 1.5 degree elevation tilt and it can be seen from (c) that there is very little clutter contamination. In the corresponding velocity images, we see that the data losses lie along the area of zero velocity intersecting the site location (zero isodop). In (c), a small amount of bias towards zero is seen near the radar because the weather is mixed with the unfiltered clutter.

This was, in fact, an extreme case with large regions of low velocity near the radar with corresponding low values of spectrum width. This is the worst case for the application of clutter filtering. Even the best filters will have problems separating weather from clutter when the mean velocities are low, power is relatively weak, and spectrum widths are narrow.

The default value for the GMAP clutter spectrum width ( $\sigma_c$ ) was identified as the probable source of the

excessive data loss. The initial deployment of ORDA used a value of 0.7 m/s for the GMAP clutter width parameter. The ORDA development team originally selected this value to attain sufficient levels of suppression. However, if the value of  $\sigma_c$  is too large, a significant number of coefficients are removed and GMAP can have difficulty rebuilding the weather signal spectrum. This appeared to have been the case for this particular stratiform rain event.

The ROC engineering team obtained Level 1 data from the ROC's test bed radar for a light stratiform rain case that occurred in central Oklahoma on December 17, 2005. The team then processed this data set using a laboratory replay capability with a number of different clutter filter settings. Variable parameters included the value of  $\sigma_c$  and the selection of time series data windowing function. Results for two of the cases replayed are shown in Figure 5.

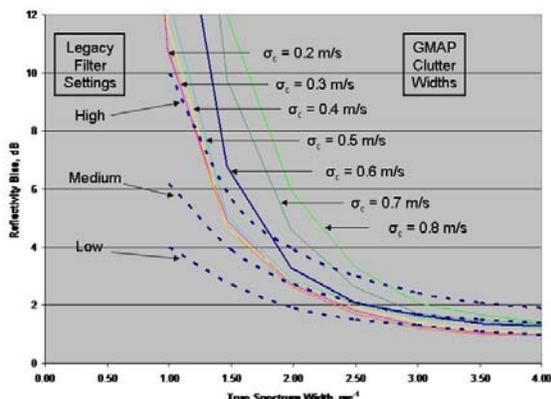


**Figure 5 - GMAP Clutter Spectrum Width Test**

Figure 5 (a) shows a reflectivity image for the 1.5 degree elevation scan using the ORDA default value of 0.7 m/s for  $\sigma_c$ . The rain was very light for this collection event. An area of data loss near the radar can be seen in the form of the familiar "butterfly" pattern which corresponds to the regions of zero velocity. The narrow region of loss to the north east is due to a water tower. Figure 5 (b) shows the same data, but re-processed with a value of 0.4 m/s for  $\sigma_c$ . Note that much of the lost

data has been restored by reducing the GMAP clutter spectrum width value.

The team then conducted extended simulations on the behavior of GMAP as a function of the clutter spectrum width value. These simulations augmented an earlier analysis (Ice et. al., 2005) by producing bias estimates for an increased range of GMAP clutter spectrum width values. Results are shown in Figure 6.



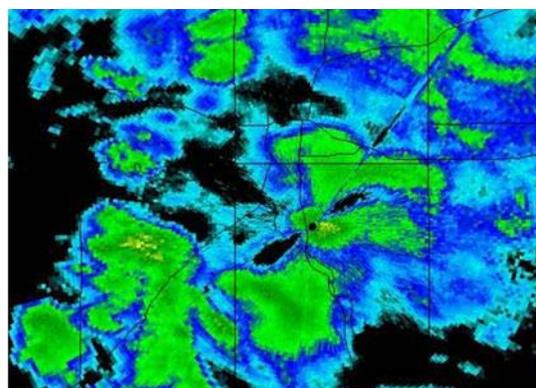
**Figure 6 - GMAP Reflectivity Bias**

The curves indicated in color correspond to different values of  $\sigma_c$  and show the amount of reflectivity bias induced by the filter as a function of weather signal spectrum width for a zero velocity weather signal. The solid curves are for values of  $\sigma_c$  from 0.2 to 0.8 m/s. For reference, the legacy data of Figure 1 is included (dashed blue lines). The bias is nearly the same for values of  $\sigma_c$  between 0.2 and 0.4 m/s. The bias data shows that the clutter width value does not greatly affect the bias as long as it is below about 0.5 m/s. Above this value, non-linear increases in the bias occur. Note that this simulation was for a worst case surveillance scan with only 16 components in the signal spectrum. This can occur in the Contiguous Surveillance scan of VCP 11. For these parameters, values of  $\sigma_c$  above 0.5 m/s cause removal of too many signal components for GMAP to properly perform the Gaussian reconstruction of the weather signal.

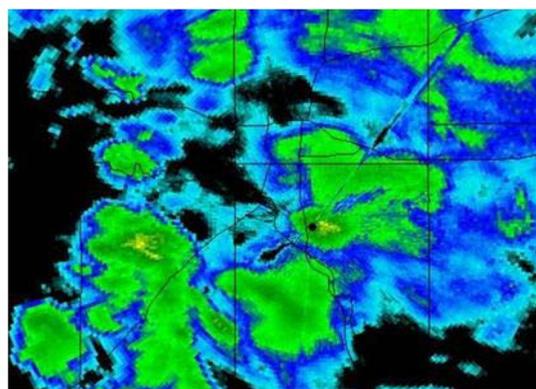
Another aspect of GMAP performance is related to the selection of time series data windowing function. The basic GMAP function, as provided by Sigmet, can make use of a number of data window types, and includes an adaptive feature that automatically selects an appropriate window based on the clutter and signal characteristics. The ROC engineering team that conducted the first evaluation of GMAP determined that the Blackman window was needed in order to attain sufficient clutter suppression levels for very strong targets (Ice et. al. 2004). Consequently, this is the default window used in the ORDA for clutter filtering. The Blackman is a very aggressive window which increases the variance of the estimates. The team would have preferred to make use of the adaptive mode which selects less aggressive windowing when possible,

but this feature does not work reliably. Even though the adaptive window is not currently used by ORDA, the engineering team ran cases using the adaptive window feature for several values of GMAP clutter spectrum width. Using the same data case and clutter width value as in Figure 5(b), Figure 7 shows a comparison of the same case for both Blackman (a) and Adaptive (b) window selections.

As can be seen in the images, the Adaptive window allows for additional data recovery, showing it may be desirable to activate this feature. However, GMAP does not always select the correct window for the clutter and weather situation, in some cases resulting in less effective suppression. The algorithm for selecting the window considers the amount of power removed by the GMAP filter as an indication of clutter strength, which determines the appropriate window. Because GMAP attempts to replace the lost weather components, the total power removed is not always a good indicator of clutter power within a bin. This process is suspected to be the reason GMAP does not always select the correct data window when the Adaptive feature is selected. For this reason, the ORDA will continue to use the Blackman window as the default for clutter filtering.

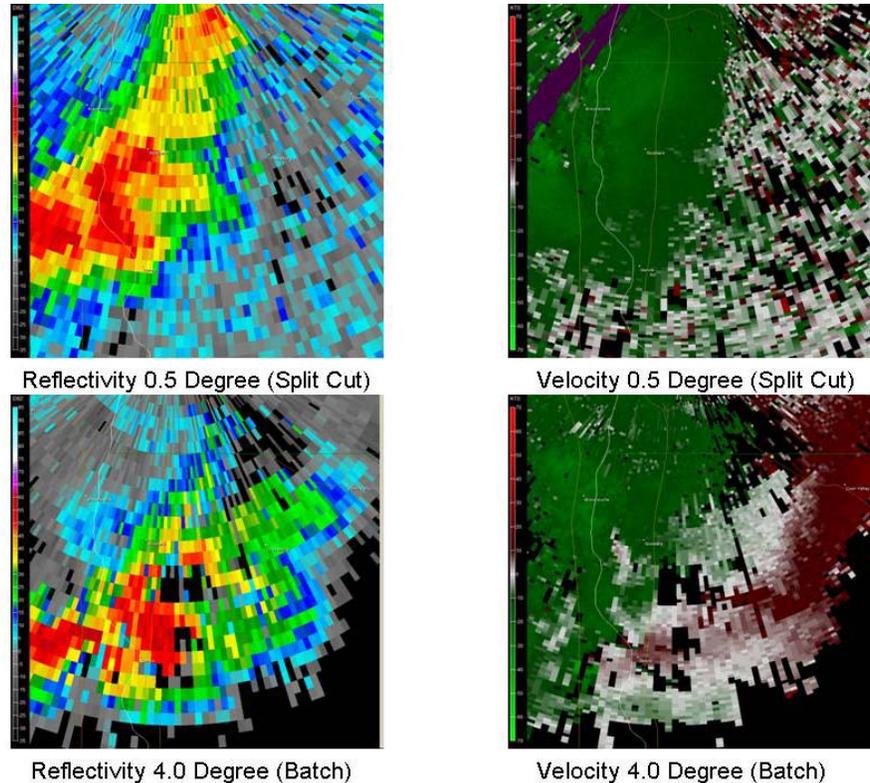


**(a) Blackman Window**



**(b) Adaptive Window**

**Figure 7 - Blackman vs. Adaptive Window**



**Figure 8 - Lower and Upper Segment Filtering**

## 6. ANALYSIS AND IDENTIFIED IMPROVEMENTS

The ROC continually monitors the quality of WSR-88D data and works to provide continuous performance improvements. While ORDA and GMAP continue to meet system specifications and generally perform better than the legacy system, improvements are possible. As a result of the GMAP clutter spectrum width parameter investigation, ROC engineers submitted a configuration change request to lower the value of  $\sigma_c$  to 0.4 m/s. This change will be incorporated in ORDA software Build 9.0 scheduled for deployment in mid 2007. The ROC test bed has been operating with this value through most of 2006. Performance in light precipitation has been improved and no adverse effects on clutter suppression have been observed.

The ROC team evaluated several other interesting cases related to clutter filter management, resulting in a second recommendation for enhancing the generation and application of clutter maps. Analysis of the following cases led to this recommendation.

In one example, a site in the upper mid-west contacted the WSR-88D Hotline because the radar was not exhibiting good continuity in reflectivity values as a function of elevation. For the case in question, reflectivity that was present in lower elevations essentially disappeared at the mid level elevations. The Hotline passed the issue on to ROC Engineering with a

request to analyze this, and other cases, where reflectivity discontinuities were occurring as a function of elevation. Engineers obtained Level 2 data for the case in question from the National Climatic Data Center (NCDC) and conducted an analysis. Figure 8 shows data used in part of the analysis.

The upper two panels of Figure 8 show the reflectivity and velocity for a portion of the data set from the lowest elevation scan. This is the 0.5 degree (split cut) data. A strong storm is observed with a corresponding inbound velocity field. Note that there are some areas of missing data in the weak reflectivity areas to the east corresponding to the application of clutter filtering via the bypass map. These missing regions to the east appear as random holes in the fields and correspond to areas of low velocity and weak signal processed by the clutter filter as selected by the site clutter map. Note that in the area of the storm with strong reflectivity, there are no missing bins because those bins contain signal with relatively high velocities.

The lower two panels show the reflectivity and velocity for the 4.0 degree elevation which is a Batch Mode tilt for this VCP. The problem that prompted the site to contact the ROC is obvious. There are a number of missing bins in both the reflectivity and the velocity images. These missing bins correspond to areas where the site clutter map has controlled the application of GMAP filtering in the upper segment. From the velocity image, engineers noted that the missing bins also have

correspondingly low velocities which results in excessive data loss from the filtering process. Analysts also noted that at 4.0 degrees, this particular site should not have significant clutter. Filtering is occurring at these elevations because the map for the second elevation segment is generated at a lower elevation and then applied to all elevations above.

With the initial ORDA deployment, only two elevation segments are available, duplicating legacy functionality. Segment 1 controls filter application for the lowest elevation angles using the split cuts (at or below 1.65 degrees) while Segment 2 controls filter application for the Batch and Contiguous Doppler cuts (above 1.65 degrees). This approach results in application of clutter filtering at all higher elevations based on the existence of clutter at the lowest elevations, resulting in excessive filtering application at higher tilts. This problem is not unique to ORDA since the design follows the legacy philosophy.

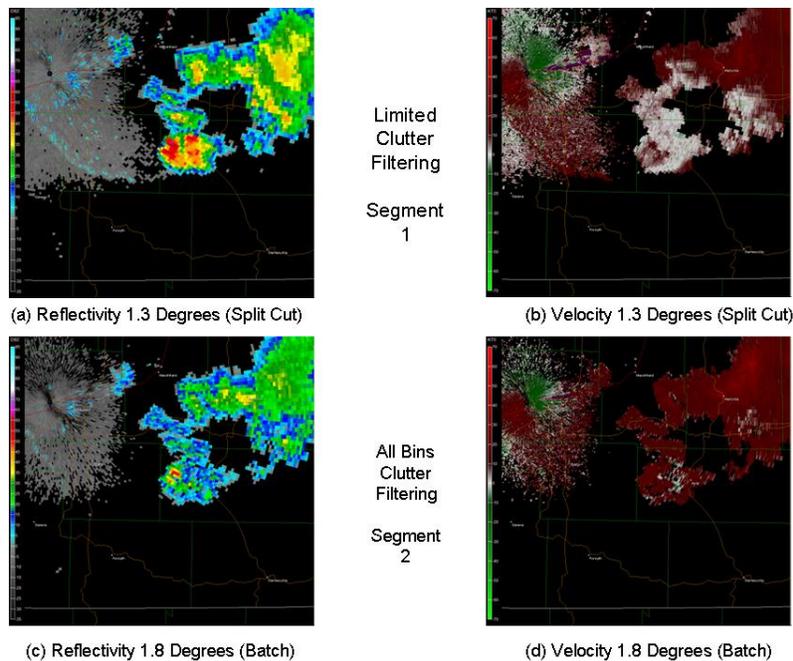
Another interesting case occurred at a mid west site that provided another lesson in managing clutter filtering. This site also noticed significant reflectivity discontinuities between lower elevations and the mid-level elevation scans and contacted the ROC. Figure 9 is representative of the initially-observed issue.

In this case, strong reflectivity is observed at the 1.3 degree elevation cut of the VCP 12 pattern (panel (a) in Figure 9). The reflectivity values drop dramatically for the next highest elevation cut at 1.8 degrees (panel (c) in Figure 9). This discontinuity does not appear natural. At first analysts suspected a flaw in the ORDA Batch Mode clutter filtering process.

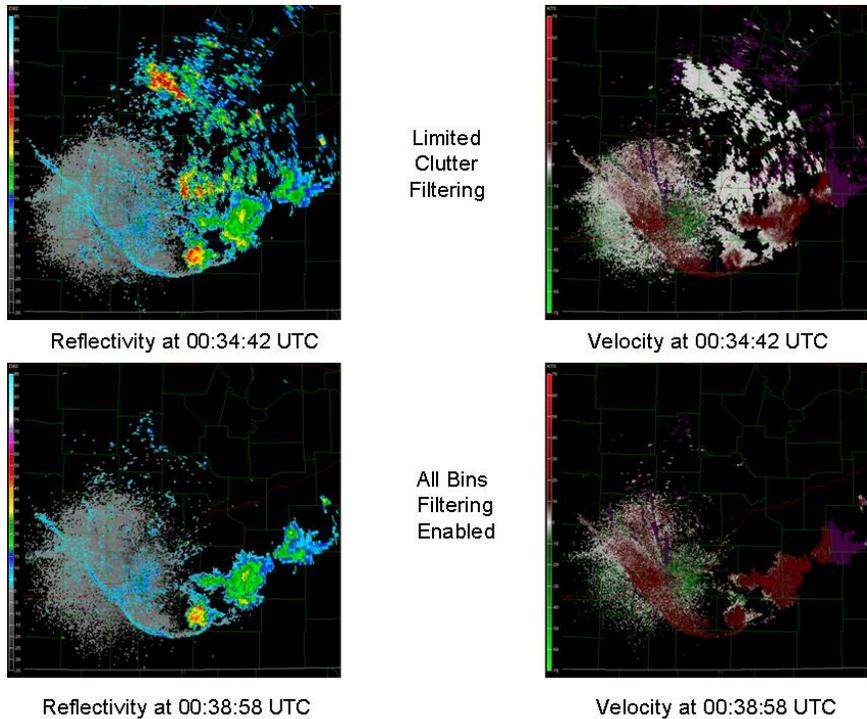
However, close examination of the velocity images associated with these scans provides a clue to the problem. Note that in panel (b) of Figure 9 there are a significant number of velocity estimates biased toward zero. This usually indicates the presence of ground clutter. At the same time, the number of near zero estimates drops significantly at 1.8 degrees, as shown in the data of panel (d). Analysts began to suspect that full clutter filtering was not being applied in the lower segment, while it was applied in the upper cut. Figure 10 sheds more light on the situation.

In Figure 10, reflectivity and velocity images are shown for two different times. In the upper two panels (00:34:42UTC), the reflectivity and velocity images contain a significant amount of AP clutter, as evidenced by the texture of the reflectivity and the predominant bias to zero in the velocity estimates to the north and east of the radar. It appears the passage of the boundary seen to the south and south west has created AP conditions behind it.

At the next VCP (00:38:58UTC) the site correctly applied all-bins filtering to clear up the AP clutter (lower two panes of Figure 10). Note that the AP clutter is removed and that the strong reflectivity values in the small storm to the south east of the radar are somewhat reduced. This reduction is due to removal of signal components associated with ground clutter. Once site operators applied clutter filtering to the lower segment in a manner consistent with filtering at the upper segment, the reflectivity discontinuities were significantly reduced.



**Figure 9 - Limited vs. All-bins Filtering**



**Figure 10 - Filtering Applied to AP Clutter**

Figure 11 shows the reflectivity estimates for the highest split cut elevation scan and the lowest batch cut scan both before and after the site operators commanded all-bins clutter filtering.

The upper two images in Figure 11 show the very obvious reduction in the reflectivity between these two contiguous scans - there was no filtering for the lower scan, but filtering was applied to the next highest scan. The two lower panels show how the fields compare after filtering was applied uniformly to both segments. While there is still a lowering of the reflectivity values as the elevation increases, the amount of change is much more in line with expected values.

Analysts reviewed data for several elevation scans to confirm proper results. Figure 12 is a comparison of the reflectivity for six elevation scans (0.5 through 3.1 degrees) for the same VCP with uniform clutter filtering applied to all elevations. As seen, there are still apparent discontinuities between the lower three split cuts and the next three batch cuts, but the differences are not nearly as dramatic as before and are possibly attributed to the natural weather structure. The results are remarkably consistent, considering the differences between Contiguous Surveillance and Batch Mode Surveillance signal processing.

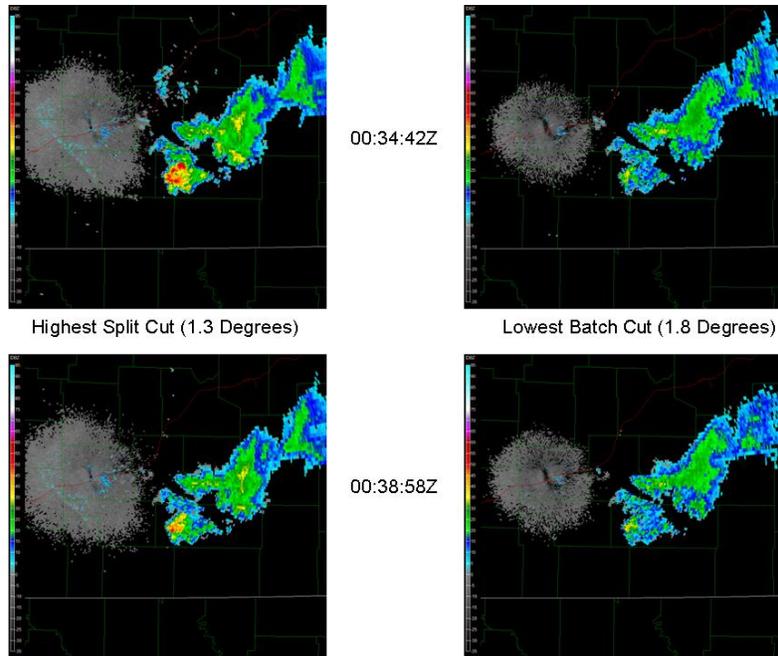
These experiences with clutter filter management prompted ROC team members to initiate a software change to better help radar operators manage clutter filtering. The ORDA can inherently support up to five clutter map segments. ROC Engineering Branch initiated a configuration change request, to be

implemented in ORDA Software Build 9.0, in mid 2007, which will allow activation of all five segments and will also establish optimal elevation angles for clutter map generation (Chrisman and Ray, 2007). This improvement should reduce elevation-dependent reflectivity discontinuities. Site operators will be able to generate clutter maps that are more appropriately matched to the normally propagated clutter fields and will have more flexibility in setting up the clutter filter application as a function of elevation angle. Proper use of the maps, with the five segments, should eliminate most issues with reflectivity discrepancies between elevation angles.

In addition to the two above-mentioned improvements, the ROC team will consider further refinements to GMAP performance. This includes optimizing values for data censoring and investigating the performance of the adaptive window feature.

## **7. INTEGRATING FILTERING WITH ADVANCED RADAR SIGNAL PROCESSING TECHNIQUES**

The WSR-88D community has been planning and developing a number of enhancements that require the ORDA capability. These new techniques can now be implemented. There are a number of clutter filtering-related aspects to the new capabilities that are discussed here. Integrating the clutter filtering process with some of the more advanced radar base moment processing techniques will be very challenging due to the complex nature of the proposed algorithms and the



**Figure 11 - Reflectivity Before and After Filtering**

need to efficiently integrate all the functions within the ORDA.

#### SZ-2 Phase Coding

The Sachidananda-Zrnic (SZ) phase coding technique is an effective algorithm for mitigating range-velocity ambiguities. NSSL developed a detailed algorithm design for implementing this approach using a specific method designated as SZ-2 (Saxion et. al., 2005). The ROC has recently implemented this algorithm and it will be deployed with ORDA software Build 9.0. This algorithm utilizes a combination of a non-phase coded surveillance scan with a low PRF to produce power estimates that are unambiguous in range. Data from this scan is used, in conjunction with phase encoded pulses from a subsequent Doppler range-ambiguous scan, to produce data that is range unfolded with greater effectiveness than what was possible with the original WSR-88D split cut unfolding technique. The improved unfolding process allows for a higher PRF to be used, thus providing much better velocity de-aliasing. The result is, for certain meteorological events, SZ-2 has much-improved signal recovery.

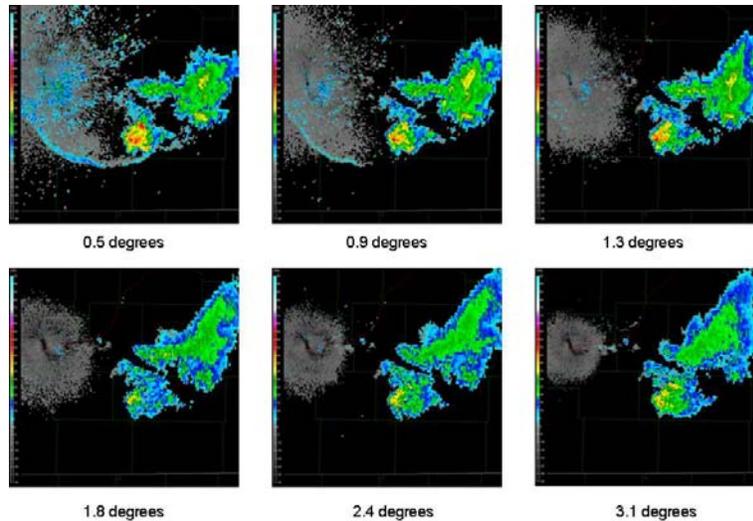
However, management of the clutter filter application will be more critical with SZ-2. SZ-2 attempts to recover the signal by examining up to four trips, producing estimates from the two strongest trips. The SZ-2 algorithm makes no attempt to recover the signal in either of the first two strong trips if clutter filtering is applied to both. This can be the case if the radar operators select all-bins clutter filtering in regions that

span more than one trip. The SZ-2 algorithm is designed to attempt an over-ride of the commanded filtering, in this case, if it can determine that there was, in fact, no clutter in the selected bins. The algorithm does this by examining the power difference between the filtered and un-filtered data streams provided by GMAP. The difference in powers must exceed a specified threshold before the SZ-2 algorithm will accept the commanded filtering, and thus not attempt a recovery.

#### Super Resolution

This enhancement will be deployed in ORDA Software Build 10.0 and will provide an option for the radar to produce data with 0.5 degree azimuthal resolution for all base moments and ¼ km range resolution in range for reflectivity (Torres and Curtis, 2007). There are two aspects of the Super Resolution design that are important for proper clutter filtering.

The increase in azimuthal resolution was initially conceived as using only one half the number of data samples for signal processing if scan rates and acquisition times are to be maintained (this is called Conventional Super Resolution). The GMAP clutter filter's performance is a function of the number of samples used for the spectral processing and for some modes, cutting the sample set in half would result in reduced performance. Also, the SZ2 algorithm places a constraint on sample acquisition because it requires 64 samples, with the current implementation.



**Figure 12 - Reflectivity Continuity Over 6 Tilts**

The Super Resolution algorithm has been designed to ensure that a sufficient number of samples are provided for these, and other, critical functions. The design provides the appropriate number of samples by actually acquiring the data over a 1.0 degree azimuth span and then aggressively windowing the time series data before computing the spectral coefficients. With this procedure, the effective beam width of the system, which is a combination of the antenna beam width and the windowing function, can be reduced from about 1.4 to 1.0 degrees (Torres and Curtis, 2006).

The second aspect of Super Resolution and clutter filtering is related to the clutter map generation and application. Super Resolution radials will be centered on  $\frac{1}{4}$  and  $\frac{3}{4}$  degree marks of the fixed 720 one-half degree intervals. The non-super resolution data from the baseline ORDA are now centered on  $\frac{1}{2}$  degree marks of the 360 one degree intervals. The existing clutter map generation and application process follows the model of the baseline ORDA. Between Super Resolution and the baseline map model, there is a  $\frac{1}{4}$  degree offset in the radial centers. Because of the distributed nature of most clutter, clutter map generation and registration with super resolution is not likely to be a significant issue. However, the analysis teams will conduct testing to ensure this aspect does not affect proper filter application and the teams will make adjustments to the mapping process, if needed.

#### Staggered PRT

The ROC has recently begun the production design and implementation phase for the Staggered PRT range-velocity ambiguity mitigation enhancement. This technique employs non-uniform spacing of the transmitted pulse in order to enhance separation of first and second trip echoes. Because successive samples are not spaced at equal time intervals, signal processing techniques that rely on uniform sampling will not work.

This includes GMAP. A new clutter filtering approach is needed before Staggered PRT can be deployed.

Fortunately, NSSL has developed a new clutter filtering technique, which can be applied to Staggered PRT (Sachindananda and Zrnice, 2006). ROC team members have begun plans for implementing and evaluating this filter as part of a phased development of Staggered PRT. However, the first phase will feature a simpler filter based on a DC signal removal technique.

#### Dual Polarization

The exact impacts of dual polarization are not known at this time, but it is likely some modifications to GMAP in the Dual Polarization mode will be needed. This will become necessary due to the need to carefully match the two channels of signal data. For example, the impact of GMAP's signal rebuilding process on Dual Polarization moment estimates is unknown and may need to be changed. Calibration for Dual Polarization is also a challenge and some researchers have been evaluating the use of ground clutter as a calibration aid. (Silberstein et. al., 2005, Zrnice et. al., 2006).

### **8. MANAGING CLUTTER FILTER APPLICATION**

The judicious application of clutter filtering, appropriate for the conditions, is one of the more important aspects of good radar data quality management. As seen in the examples here, inconsistent filter application, or rapidly changing propagation conditions, can adversely affect data quality. Teams at the ROC, NSSL and NCAR have been working to provide better tools for field operators to help them more effectively manage filtering operations.

#### Radar Echo Classifier (REC)

The REC was the first clutter filter management tool to become available and has been a part of the WSR-

88D algorithm suite for some time (Kessinger et al., 2005). It consists of a fuzzy-logic based scheme that uses the three basic radar moments as inputs. The algorithm delivers a product available to the operator that identifies probable areas of clutter for each volume scan. The operator can then choose to manually alter the clutter filter settings to address the clutter. The REC does not incorporate any automated filter management schemes, but does provide input for the precipitation algorithms.

#### Clutter Mitigation Decision (CMD)

The next phase in clutter filter management will provide for the automatic application of clutter filters in the ORDA based on the CMD algorithm (Dixon et al., 2005 a, b). One problem with the use of spectral clutter filters is that, as mentioned earlier, clutter in the spectral domain looks very similar to stratiform precipitation with a narrow spectrum width and a velocity close to zero. If applied everywhere, the filter will remove non-clutter power from the weather signal in regions where these conditions occur.

In order to overcome this problem, it is necessary to deduce the likelihood of clutter, using information independent of that used by the filter. Examples of such information are: (a) the spatial texture of the reflectivity field, (b) the variability of the pulse-to-pulse power at a gate (Tatehira and Shimizu, 1978), and (c) if dual polarization data is available, the spatial variability of Differential Reflectivity ( $Z_{DR}$ ) and Differential Phase ( $\Phi_{DP}$ ).

The NCAR CMD uses this information, along with base moments, to determine the likelihood of clutter contamination for every bin. This clutter likelihood parameter can then be used to update baseline clutter maps, automatically applying filtering to bins which become contaminated by clutter due to changing propagation conditions. The ROC has begun designing the production implementation of the NCAR CMD algorithm with deployment currently scheduled for software Build 13.0.

To support early evaluations and production design analysis, ROC Engineering implemented the NCAR algorithm in MATLAB (Warde et. al., 2007). Using time series data from normal WSR-88D scans, the MATLAB tool can produce a clutter map which can be applied in the laboratory to an RVP8 when the same time series data set is played back to produce Level 2 moment estimate data.

Figure 13 shows the results of an early analysis on the performance of the laboratory CMD tool. Note that the clutter map and the radar data image are not to the same scale. On the left side (a), upper panel, is a clutter map generated via the normal WSR-88D radar test software suite. Below that is a corresponding reflectivity image processed from time series data and using that normally generated map to apply clutter filtering. This clutter map was generated by the Radar System Test Software (RSTS) mode on the live radar and uses a special scan which ensures high resolution of clutter returns. It must be run during specific weather conditions. The data set shown was known to contain

AP clutter. As can be seen, applying a normal propagation map to AP-clutter contaminated data results in poor filtering of the AP-clutter.

The upper right panel of Figure 13, shows a map generated by CMD from the same set of data. The map is the output of a MATLAB based analysis tool developed by ROC Engineering from the algorithm description provided by NCAR. The CMD map is generated from the time series data using an operational VCP. The reflectivity estimate field shown below the map was produced using the same time series data set, but with the CMD map determining filter application. As can be seen, the CMD-controlled filter application eliminates the AP-clutter and cleans up the display.

ROC engineers continue to develop tools for the CMD project and will address specific implementation design details in the coming year. Some aspects of the production design will include decisions about the need for real-time bin-by-bin determination of clutter filter control. It may be that the most efficient implementation will be to use CMD to update the system clutter maps each VCP, rather than on the fly for every data bin. The design team will conduct the necessary trade-off analysis and will validate the selected approach using the laboratory playback and analysis tools on radar time series data.

NCAR scientists are also improving the CMD design, adding new inputs and streamlining the required processing which will ease implementation into the ORDA signal processing functions.

## **9. CONCLUSION**

With the completed deployment of the ORDA in October 2006, many new options for radar performance enhancement are now possible. An important aspect of these new capabilities is the optimization of clutter filtering. Early experience with the ORDA has led to some near-term improvements such as adjustment of the GMAP clutter spectrum width parameter and the addition of multiple map segments.

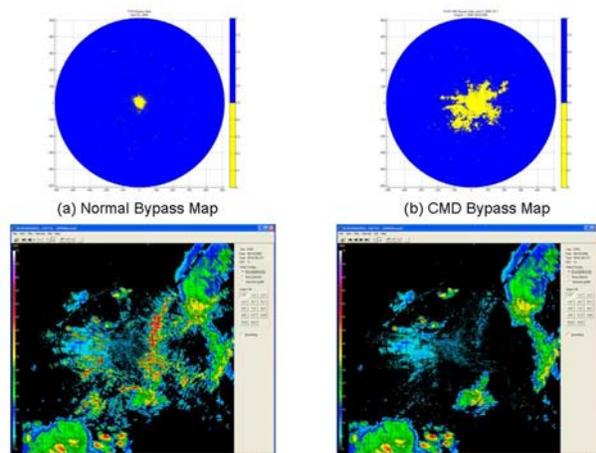
ROC team members, from both the scientific and engineering disciplines, plan to continue efforts to monitor clutter filter performance and will work to identify and implement additional improvements. The teams will continue to optimize the integration of clutter filtering into new science enhancements as they are approved for the WSR-88D network. The addition of CMD to the system will provide a significantly enhanced capability to manage the filtering process.

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our efforts to optimize clutter filter performance and application guidance.



**Figure 13 – Normal and CMD Bypass Maps**

## 11. REFERENCES

- Chrisman, J. N., and C. A. Ray, 2005, A First Look at the Operational (Data Quality) Improvements Provided by the Open Radar Data Acquisition (ORDA) System, 32<sup>nd</sup> Conference on Radar Meteorology.
- Chrisman, J. N., and C. A. Ray, 2007, A Method to Reduce the Clutter Filter Induced Data Bias by Improving the Vertical Application of WSR-88D Bypass Maps, 23<sup>rd</sup> International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
- Dixon, M., C. Kessinger, and J. C. Hubbert, 2005a, Echo Classification Within the Spectral Domain to Discriminate Ground Clutter from Meteorological Targets, 2005b, 22<sup>nd</sup> International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
- Dixon, M., C. Kessinger, and J. C. Hubbert, 2005b, Echo Classification and Spectral Processing for the Discrimination of Clutter from Weather, 32<sup>nd</sup> Conference on Radar Meteorology.
- Free, A. D., and N. K. Patel, 2005, Clutter Censoring Theory and Application for the WSR-88D, 32<sup>nd</sup> Conference on Radar Meteorology.
- Ice, R. L., R. D. Rhoton, D. S. Saxion, N. K. Patel, D. Sirmans, D. A. Warde, D. L. Rachel, and R. Fehlen, 2004, Radar Operations Center Evaluation of the WSR-88D Open Radar Data Acquisition (ORDA) System Signal Processing, 20<sup>th</sup> International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
- Ice, R. L., G. T. McGehee, R. D. Rhoton, D. S. Saxion, D. A. Warde, R. G. Guenther, D. Sirmans, and D. Rachel, 2005, Radar Operations Center (ROC) Evaluation of New Signal Processing Techniques for the WSR-88D, 21<sup>st</sup> International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
- Kessinger, C., S. Ellis, J. Van Andel, J. Yee and J. Hubbert, (2005), The AP Ground Clutter Mitigation Scheme for the WSR-88D, 21<sup>st</sup> International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
- Passarelli, R., and A. Siggia, 2004, Gaussian Model Adaptive Processing for Improved Ground Clutter Cancellation and Moment Estimation, Third European Conference on Radar Meteorology and Hydrology.
- Sachidananda, M. and D. S. Zrnica, 2006, Ground Clutter Filtering Dual-Polarized, Staggered PRT Sequences, Journal of Atmospheric and Oceanic Technology, Volume 23.
- Saxion, D. S., R. D. Rhoton, G. T. McGehee, R. L. Ice, D. A. Warde and D. Sirmans, 2005, Radar Operations Center (ROC) Production Software Status for RV Ambiguity Mitigation, 21<sup>st</sup> International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
- Silberstein, D. S., D. B. Wolf, D. A. Marks and J. L. Pippitt, 2005, Using Ground Clutter to Adjust Relative Radar Calibration at Kwajalein, RMI, 32<sup>nd</sup> Conference on Radar Meteorology.
- Sirmans, D., Clutter Filtering in the WSR-88D, 1992, Internal Report, WSR-88D Operational Support Facility (available from the WSR-88D Radar Operations Center, Norman OK)
- Tatehira, R., and T. Shimizu, 1978: Intensity measurement of pre-cipitation echo superposed on ground clutter--A new automatic technique for ground clutter rejection. Preprints, 18th Conf. on Radar Meteorology, Atlanta, GA, Amer. Meteor. Soc., 364 -369.

- Torres, S. and Y. Dubel, 2004, Design, Implementation, and Demonstration of a Staggered PRT Algorithm for the WSR-88D, *Journal of Atmospheric and Oceanic Technology*, Volume 21.
- Torres, S. and C. Curtis, 2007, Initial Implementation of Super Resolution Data on the NEXRAD Network, 21<sup>st</sup> International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
- Torres, S. and C. Curtis, 2006, Design Considerations for Improved Tornado Detection Using Super-resolution Data on the NEXRAD Network. Preprints, Third European Conf. on Radar Meteorology and Hydrology (ERAD), Barcelona, Spain, Copernicus.
- Warde, D. A., R. L. Ice, R. D. Rhoton, D. S. Saxion, O. E. Boydston, D. S. Berkowitz, M. Dixon, 2007, Clutter Mitigation Decision System Performance Evaluation in the WSR-88D, 23<sup>rd</sup> International Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology.
- Zrnic, D. S., V. Melnikov and A. Ryzhkov, 2006, Correlation Coefficients between Horizontally and Vertically Polarized Returns from Ground Clutter, *Journal of Atmospheric and Oceanic Technology*, Volume 23.