3.0 Compensating Reflectivity for Clutter Filter Bias

3.1 Introduction

The presence of anomalous propagation (AP) and normal propagation (NP) ground clutter presents serious problems for radar precipitation estimation and prediction. The high reflectivity (Z) ground echoes are frequently misinterpreted as rainfall by reflectivity-based estimation algorithms, leading to substantial overestimates of rainfall amounts. This can lead to false automated flash flood warnings and overestimates of runoff, adversely effecting a wide variety of end users.

Ground clutter is characterized by narrow spectrum width (W) and near-zero radial velocity (V). Clutter filters are able to cancel ground clutter in most situations by effectively removing the spectral power near zero velocity. When the clutter filters are used in weather echoes having low radial velocity, power is also removed from the weather echoes, resulting in a negative reflectivity bias (Sirmans 1992, Cornelius et al. 1995). To obtain accurate radar-estimated rainfall amounts, the ground clutter contamination must be removed with clutter filters and the resulting precipitation reflectivity bias must be corrected.

Clutter filtering causes significant biases in both V and W as well as reflectivity (Sirmans, 1992). Correction of these biases is also possible; however, in this report, only the correction of Z and V is addressed.

The Reflectivity Compensation Scheme (RCS) (Cornelius et al. 1995; Ellis 2001, included as Appendix B) is a part of the AP Clutter Mitigation Scheme (Keeler et al., 1999). This scheme includes identifying echo type with the Radar Echo Classifier (REC) (described in Section 2.0) and selectively applying ground clutter filters to the clutter-contaminated regions. The selective application of the clutter filters will reduce the impact of clutter filter bias on precipitation echoes. Reflectivity compensation is an essential part of any comprehensive AP clutter mitigation scheme because cases of mixed clutter and precipitation echoes are common, and necessitate the use of the clutter filters in weather data.
The RCS method is tested on WSR-88D data. In-phase and quadrature (I and Q) data (also called Archive 1 or time series data) are processed using autocovariance calculations and clutter filters that emulate the WSR-88D processor. Both filtered and unfiltered moment data are available for verification of the RCS method. The processing includes quantizing the Z, V, and W data to be similar to WSR-88D output. The filtered and unfiltered data streams are not available simultaneously in the WSR-88D system. In "pure" precipitation situations, the unfiltered data stream provides the truth field for verification of the method. With both data streams available for our testing, the clutter filter bias can be determined and the ability of the compensation method to remove it can be measured.

3.2 Data

The data used here are WSR-88D time series data collected with NCAR’s Archive 1 Data Acquisition (A1DA) unit (Keeler et al., 1998). The A1DA was deployed at the Memphis WSR-88D (KNQA) during the summer of 1997 to support the development and testing of an AP clutter mitigation algorithm. Analyses are presented for three plan position indicator (PPI) scans.

The data are from stratiform rain containing low radial velocity values. This situation is conducive to severe clutter filter bias because stratiform rain typically has small spectrum width values. This stratiform data, with small V and W values, represents a worst-case scenario for clutter filter biases and is an ideal case for a stringent evaluation of the RCS method.

The pulse-pair algorithm is used to compute both the clutter filtered and unfiltered moments from the time series data. Processing the time series data off line allows retention of both filtered and unfiltered data streams, which is not currently an option on the WSR-88D. Both data streams are essential to verify the results from the technique.

The radar constant and range corrections are not applied to the power field to obtain calibrated reflectivity data because the correction for range and radar constant do not change the reflectivity compensation value. Also, the difference between the unfiltered
and filtered (or compensated) power fields is the same as the differences in reflectivity units. Thus, the performance statistics and compensation values are independent of the process to obtain reflectivity from power. We refer to the power as $P$, however for our purposes it can be considered analogous to reflectivity, $Z$. For presentation, the values of $P$ are converted to dB space relative to the measured I and Q data, which we refer to as dBX.

Applying the pulse-pair algorithm to time series data does not result in moment estimates ($P$, $V$ and $W$) having the resolution of current WSR-88D Archive 2 output. Therefore, the derived base data are quantized to emulate WSR-88D data. This includes quantizing $V$ and $W$ data to 0.5 m $s^{-1}$ bins and quantizing $P$ to 0.5 dB bins. The range resolution for $P$ is also degraded to 1 km by choosing the maximum value over 1 km, as is done in the WSR-88D. Separate scans with different pulse repetition frequencies for Doppler data ($V$ and $W$) and power estimates ($P$) are not used in these experiments, as is done in the WSR-88D scanning strategy. Previous experiments (Kessinger et al., 1999) did not attempt to match the data resolution of the WSR-88D output levels and it was not known what effect the quantization would have on algorithm performance.

Special care was taken to ensure that the data used are free of ground clutter contamination. "Pure" precipitation echo is desirable because the truth field is then defined as the unfiltered data. In pure precipitation echo, after applying the clutter filter, a perfect reflectivity compensation method should return the unfiltered values. However, if ground clutter contamination exists, the proper compensated value is not known. To help ensure the data are clutter free, data from the 1.5 degree elevation angle data are chosen rather than the 0.5 degree scans only after the base data are carefully examined. Also, a sample of the Doppler spectra for individual gates is also examined. In the spectral data, ground clutter is easily recognized as a power spike at 0 m $s^{-1}$ radial velocity. An example of a precipitation spectra for one gate of radar data containing 64 pulses is shown in Fig. 3.1. The precipitation spectra is clearly visible with a velocity near $+5$ m $s^{-1}$. No clutter spike at 0 m $s^{-1}$ velocity is visible.
Figure 3.1. Example of precipitation spectra from one of the analyzed data sets. Notice the absence of a clutter spike at 0 m s$^{-1}$ radial velocity.

3.3 The Compensation Technique

The method uses "look-up" tables of corrections that have been generated a-priori, making it computationally efficient. The corrections are computed using Gaussian approximations for precipitation spectra and a simulated clutter filter consistent with the characteristics of the real clutter filter used by the radar. Each clutter filter configuration requires a separate table of corrections. It is straight-forward to obtain filtered and unfiltered power as well as filtered radial velocity and spectrum width from the simulated data, from which the look-up tables are constructed.

The first step in creating the look-up table is to generate a family of Gaussian spectra, $S_u$, using,

$$
|S_u(V)| = \exp\left(-\frac{(V - \bar{V})^2}{2\sigma_v^2}\right)
$$

Eq. 3.1

where $\bar{V}$ and $\sigma_v$ are the input (unfiltered) radial velocity and spectrum width and $V$ is the velocity spectrum. Numerous spectra are computed using $\bar{V}$ and $\sigma_v$ inputs that span a range of physically relevant values. In our case the ranges were, $-10 > \bar{V} > 10$ m s$^{-1}$ and
\[ 0 > \sigma_v > 10 \text{ m s}^{-1}. \] The unfiltered power \( (M_0) \) is estimated as

\[ M_0 = \int_{-\infty}^{\infty} S_a(V) dV \]  \hspace{1cm} \text{Eq. 3.2} 

Next, the corresponding filtered power \( (M_{0\text{filt}}) \), filtered velocity \( (V_{\text{filt}}) \) and filtered spectrum width \( (W_{\text{filt}}) \) are calculated for each spectrum using the following moment calculations,

\[ M_{0\text{filt}} = \int_{-\infty}^{\infty} |S_a(V)| h(V) dV \]  \hspace{1cm} \text{Eq. 3.3} 

\[ V_{\text{filt}} = \int_{-\infty}^{\infty} V |S_a(V)| h(V) \frac{dV}{M_{0\text{filt}}} \]  \hspace{1cm} \text{Eq. 3.4} 

\[ W_{\text{filt}} = \sqrt{\int_{-\infty}^{\infty} (V - V_{\text{filt}})^2 |S_a(V)| h(V) \frac{dV}{M_{0\text{filt}}}} \]  \hspace{1cm} \text{Eq. 3.5} 

where \( h(V) \) is a piecewise-continuous function designed to emulate the WSR-88D clutter filter response (Fig. 3.2). The power estimates from equations 3.2 and 3.3 are unit-less linear quantities.

The passband velocity \( (V_p) \) and stopband velocity \( (V_s) \) are selected using the reported filter response characteristics of the three WSR-88D clutter filter configurations listed in Table 3.1 (Sirmans, 1992). The notch depth of the WSR-88D filters is 60 dB.

Finally, the correction factor for \( Z (L) \) is computed as the ratio

\[ L = \frac{M_0}{M_{0\text{filt}}}. \]  \hspace{1cm} \text{Eq. 3.6} 

Thus, we end up with one table for each filter configuration consisting of \( V_{\text{filt}}, W_{\text{filt}}, L \)
and $\bar{V}$ values spanning the range of $\bar{V}$ and $\sigma_v$ inputs. The measured $V$ and $W$ pair (recall these are filtered values) is then matched to the nearest $V_{\text{filt}}$ and $W_{\text{filt}}$ pair from the proper look-up table to obtain the corresponding reflectivity correction factor, $L$, and the corrected radial velocity, $V_{\text{comp}} = \bar{V}$. The corrected power is computed by multiplying the measured power by $L$. Note that all of the computations on power are performed in linear space, and that the correction factor is independent of the range correction and radar constant used to convert power to reflectivity. The corrected value of radial velocity is obtained by substituting the table value $\bar{V}$ for the measured filtered radial velocity.

Figure 3.3 shows an example of the computation of a correction value for one Gaussian precipitation spectra approximation. Figure 3.3a depicts the unfiltered Gaussian spectrum

<table>
<thead>
<tr>
<th>Velocity</th>
<th>Clutter Filter Suppression Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>$V_s$ (m/s)</td>
<td>0.7095</td>
</tr>
<tr>
<td>$V_p$ (m/s)</td>
<td>1.825</td>
</tr>
</tbody>
</table>

Table 3.1. Stopband ($V_s$) and passband ($V_p$) edge velocities (see Fig. 3.1) for the low, medium, and high suppression WSR-88D clutter filters.
computed from Eq. 3.1 with an input velocity of $V_0 = 1.0 \text{ m s}^{-1}$ and spectrum width $W = 2.0 \text{ m s}^{-1}$. The unfiltered power is computed from Eq. 3.2 as $M_0 = 2.54$. Figure 3.3b shows the results of the filtered moment calculations (Eqs. 3.3 – 3.5) for the spectrum depicted in Fig. 3.3a. Compared to the unfiltered power the filtered power estimate is reduced to $M_{0\text{filt}} = 1.85$ due to the removal of power near-zero m s$^{-1}$ by the clutter filter. It can also be seen that the filtered radial velocity, $V_{\text{filt}}$, is biased in the positive direction (away from zero m s$^{-1}$) to $1.73 \text{ m s}^{-1}$ and the filtered spectrum width $W_{\text{filt}}$ is biased high to $2.54 \text{ m s}^{-1}$, as a result of applying the clutter filter to the Gaussian spectrum. In this example, $L = 1.85$ in linear space which is equivalent to 2.65 dB.

It has been shown that this method produces some unrealistically large correction factors when the clutter filter has removed the vast majority of the Gaussian spectra, $S_u(V)$ (Kessinger et al., 1999). A maximum correction value, $L$, of 31.62 (equivalent to 15 dB) is applied to the radar data. If the computed value of $L$ for an observation exceeds this value the correction factor is not applied and the gate is flagged to be "hole-filled" after the surrounding observations are compensated. A two-dimensional median filter is used as the hole-filling technique.

As noted in Section 3.2 the resolution of the power data is degraded to 1 km resolution,
while the Doppler data has 0.25 km resolution. This means that for every observation of power, there are four observations of radial velocity and spectrum width, creating the question of how to use these data sets, with differing resolutions, together. For each power observation the compensation method is performed four times, once for each Doppler observation it contained. The compensated power then has a resolution of 0.25 km, that is degraded to 1 km by using the median of the four values. The compensated power is also quantized to 0.5 dB to bins as is done in the current WSR-88D output. A 0.5 m s\(^{-1}\) quantization is applied to the corrected value of radial velocity as well.

3.4 Results of the Reflectivity Compensation Tests

The RCS method is validated using the WSR-88D time-series data discussed in Section 3.2. Recall that both the filtered and unfiltered moment data are available and that, in the absence of clutter contamination, the unfiltered data provides the truth field for the correction methods. The biases, \(B\), for filtered and compensated power are computed as follows,

\[
B_x = 10 \log_{10} \left( \frac{\sum P_u / P_x}{N} \right), \hspace{1cm} \text{(dB)} \hspace{1cm} \text{Eq. 3.7}
\]

and the standard errors, \(SE\), were calculated using,

\[
SE_x = \sqrt{\frac{\sum \left[ (P_u / P_x) - (P_u / P_x) \right]^2}{N}}, \hspace{1cm} \text{(dB)} \hspace{1cm} \text{Eq. 3.8}
\]

where \(N\) is the number of gates, \(P_u\) is the linear unfiltered power and \(P_x\) is the linear filtered, or compensated power.

Section 3.3 of Kessinger et. al. (1999) showed that the compensation method performed poorly when the high suppression clutter filter configuration was used and recommended that it only be used in the absence of precipitation, when no reflectivity compensation is
Table 3.2. Power biases (dB) for the filtered and compensated (Comp) power estimates using the WSR-88D medium suppression clutter filter configuration. The biases were computed in linear space then converted to dB.

| Case  | $|V| < 3$       | $|V| < 1.5$       |
|-------|----------------|------------------|
|       | Filtered       | Comp             | Filtered       | Comp             |
| Case 1| -1.82          | -0.13            | -2.25          | -0.24            |
| Case 2| -1.89          | -0.02            | -2.74          | -0.06            |
| Case 3| -2.91          | -0.41            | -3.59          | -0.43            |

performed. Because the results for the medium and low suppression filters are very similar for the data considered here, only the results from the medium suppression filter are presented.

Table 3.2 lists the power biases computed over two ranges of overlapping velocity data, $|V_{unfilt}| < 3.0 \text{ m s}^{-1}$ and $|V_{unfilt}| < 1.5 \text{ m s}^{-1}$ for three separate cases using the medium suppression clutter filter configuration (Sirmans 1992). These velocity ranges near $0 \text{ m s}^{-1}$ contain the largest clutter filter bias, as well as the greatest uncertainty in the compensated estimate. The clutter filter induced reflectivity bias is reduced to values on the order of tenths of one dB after the compensation method is applied. Table 3.3 lists the standard error statistics for the same three cases. An important result is that the standard error of the compensated power estimate is reduced from the filtered estimate by about a factor of two. This implies that, not only does the compensation remove the bias, but the uncertainty of the estimate at a given gate also decreases in comparison with the filtered estimate.

Table 3.4 lists the radial velocity biases computed for two ranges of velocity values, $-1.5 < V_{unfilt} < 0 \text{ (m s}^{-1})$ and $0 < V_{unfilt} < 1.5 \text{ (m s}^{-1})$. The clutter filter bias is positive for $V_{unfilt} > 0 \text{ m s}^{-1}$ and negative for $V_{unfilt} < 0 \text{ m s}^{-1}$, thereby dictating that the analysis be performed separately for positive and negative velocity values. The clutter filter induced $V$ bias has a magnitude of approximately $0.5$ to $0.75 \text{ m s}^{-1}$ and is reduced to $\leq 0.2 \text{ m s}^{-1}$.
Table 3.3. Standard error in power (dB) for the filtered and compensated (Comp) power estimates using the WSR-88D medium suppression clutter filter configuration.

|        | $|V| < 3$ |        | $|V| < 1.5$ |
|--------|---------|--------|------------|
|        | Filtered| Comp   | Filtered   | Comp   |
| Case 1 | 0.83    | 0.46   | 1.01       | 0.53   |
| Case 2 | 1.00    | 0.55   | 1.35       | 0.77   |
| Case 3 | 1.66    | 0.91   | 1.92       | 1.07   |

Table 3.4. Biases (m s$^{-1}$) for filtered and compensated radial velocity using the WSR-88D medium suppression clutter filter configuration.

<table>
<thead>
<tr>
<th></th>
<th>$1.5 &gt; V &gt; 0$</th>
<th></th>
<th>$-1.5 &lt; V &lt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Filtered</td>
<td>Comp</td>
<td>Filtered</td>
</tr>
<tr>
<td>Case 1</td>
<td>0.51</td>
<td>0.11</td>
<td>-0.42</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.70</td>
<td>0.10</td>
<td>-0.76</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.45</td>
<td>-0.10</td>
<td>-0.75</td>
</tr>
</tbody>
</table>

by the compensation method. The fact that the method removes the clutter filter induced biases in both reflectivity and radial velocity suggests that the look-up tables contain realistic values and that the assumptions made in creating them are reasonable.

The reflectivity compensation statistics are re-computed for $P_{\text{unfilt}} > -25$ dBX, which is approximately equivalent to reflectivity values above $\sim 25$ dBZ. Recall that unit of dBX is relative to the measured I and Q data. This additional analysis ensures that the compensation method has good performance in regions of reflectivity values used for
| $P_{\text{unfilt}} > -25 \text{ dBX}$ | $|V| < 3$ |       |       |
|---|---|---|---|
|       | Filtered | Comp |       |
|       |       |       |       |
| Case 1 | -1.84 | 0.00 | -2.25 |
|       |       |       | -0.1  |
| Case 2 | -1.75 | 0.41 | -2.37 |
|       |       |       | 0.66  |
| Case 3 | -2.73 | 0.40 | -3.15 |
|       |       |       | 0.79  |

Table 3.5. Power biases (dB) for the filtered and compensated (Comp) power estimates using the WSR-88D medium suppression clutter filter configuration. Only data with $P_{\text{unfilt}} > -25 \text{ dBX}$ are considered.

| $P_{\text{unfilt}} > -25 \text{ dB}$ | $|V| < 3$ |       |       |
|---|---|---|---|
|       | Filtered | Comp |       |
|       |       |       |       |
| Case 1 | 0.75 | 0.42 | 0.91  |
|       |       |       | 0.50  |
| Case 2 | 0.80 | 0.45 | 1.02  |
|       |       |       | 0.55  |
| Case 3 | 1.06 | 0.64 | 1.13  |
|       |       |       | 0.70  |

Table 3.6. Standard error in power (dB) for the filtered and compensated (Comp) power estimates using the WSR-88D medium suppression clutter filter configuration.

radar-based precipitation rate estimates. Table 3.5 lists the biases and Table 3.6 lists the standard errors for $P_{\text{unfilt}} > -25 \text{ dBX}$. The magnitude of the biases in $P_{\text{comp}}$ are increased for the high power values for Cases 2 and 3 and decreased for Case 1 when compared to Tables 3.2 and 3.3. The biases never exceed 1 dB, and are near or less than 0.5 dB, the resolution of the power estimates. Thus, the precipitation values may be compensated to about the same uncertainty as that induced by the 0.5 dB quantization. Figure 3.4 shows PPI’s from Case 1 of unfiltered power ($P_{\text{unfilt}}$), filtered power ($P_{\text{filt}}$), compensated power
Figure 3.4. PPI displays for Case 1 of a) unfiltered power, b) filtered power, c) compensated power and d) compensated power error (compared to unfiltered power).

(P_{comp}) and the compensation errors. Recall that the errors are computed as $10\log_{10}(P_{comp} / P_{unfilt})$. Comparing Figs. 3.4a and 3.4b, the clutter filter bias is evident (see also Table 3.2). Figure 3.4c shows that the method successfully removed the bias in a mean sense. Some observations are over-compensated and some observations are under-compensated, as is expected from the standard error statistics (Table 3.3). Figure 3.4d shows that the magnitude of the error varies from region to region. This is expected because the radial velocity and spectrum width values vary in space and will effect the
Figure 3.5. PPI displays for Case 1 of a) radial velocity (m s\(^{-1}\)), b) spectrum width (m s\(^{-1}\)) for \(-2 < V_{\text{unfilt}} < 2\) (m s\(^{-1}\)). The correction factor (dB) is plotted in c) and the gates that exceeded the 15 dB correction threshold in d).

The magnitude of the clutter filter bias. The radial velocity and spectrum width for \(-2 < V_{\text{unfilt}} < 2\) (m s\(^{-1}\)) from Case 1 are plotted in Fig. 3.5a and 3.5b, respectively. Regions of low velocity and low spectrum width contain the largest clutter filter biases and therefore should have the largest correction factors. The values of the corresponding correction factors, L (dB), are plotted in Fig. 3.5c. Clearly, the areas with the largest corrections correspond to areas with low radial velocity combined with low spectrum width. Not surprisingly, these regions have the greatest magnitude of error (Fig. 3.4d). The points in which L exceeded the 15 dB threshold and were hole-filled using surrounding data are
Figure 3.6. PPI plots of a) unfiltered, b) filtered and c) corrected radial velocity (m s$^{-1}$). The difference field $V_{\text{comp}} - V_{\text{unfilt}}$ is plotted in part d).

Figure 3.6 shows PPI’s, from Case 1, of unfiltered radial velocity, filtered radial velocity, corrected radial velocity and the difference field of $V_{\text{comp}} - V_{\text{unfilt}}$. Comparing Figs. 3.6a and 3.6b carefully, the bias of V away from zero can be seen. Gates with positive $V_{\text{unfilt}}$ have positively biased $V_{\text{filt}}$ values (warm colors become warmer) and gates with negative $V_{\text{unfilt}}$ have negatively biased $V_{\text{filt}}$ values (cool colors become cooler). The corrected velocity ($V_{\text{comp}}$), depicted in Fig. 3.6c, retrieves $V_{\text{unfilt}}$ reasonably well (see...
Figure 3.7. Scatter plots of errors in a) clutter filtered power and b) compensated power as a function of radial velocity.

![Scatter plots of errors in a) clutter filtered power and b) compensated power as a function of radial velocity.](image)

Figure 3.8. Scatter plots of a) clutter filtered radial velocity and b) compensated radial velocity as a function of radial velocity.

![Scatter plots of a) clutter filtered radial velocity and b) compensated radial velocity as a function of radial velocity.](image)

Table 3.4). The difference field (Fig. 3.6d) shows that $V_{\text{comp}}$ is generally within 1 m s$^{-1}$ of $V_{\text{unfilt}}$.

To visualize the characteristics of the clutter filter and compensation, scatter plots of $(P_{\text{filt}} - P_{\text{unfilt}})$ versus $V_{\text{unfilt}}$ and $(P_{\text{comp}} - P_{\text{unfilt}})$ versus $V_{\text{unfilt}}$ are plotted in Figs. 3.7a and 3.7b, respectively. Not surprisingly the magnitude of the error is greatest near 0 m s$^{-1}$ radial velocity for both filtered and compensated power. The variance of $P_{\text{comp}}$ near 0 m s$^{-1}$ remains high, however the bias is clearly removed. Figure 3.8 shows scatter plots of $V_{\text{filt}}$ versus $V_{\text{unfilt}}$ and $V_{\text{comp}}$ versus $V_{\text{unfilt}}$. The bias away from 0 m s$^{-1}$ introduced by the

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Figure 3.9. Histograms of a) unfiltered, b) filtered and c) compensated power for Case 1 data with $P_{\text{unfilt}}> -25 \text{ dBX}$ and $|V_{\text{unfilt}}| < 3 \text{ m s}^{-1}$. Mean powers are a) $-17.03 \text{ dBX}$, b) $-18.57 \text{ dBX}$ and c) $-16.75 \text{ dBX}$.

correction filter is apparent in Figs 3.8a. The corrected radial velocities nearly remove the bias (Fig. 3.8b). There are many data points overplotted in Figs. 3.7 and 3.8 due to the quantization of the data, making it impossible to ascertain data density. The scatter-plots are more useful when considered in parallel with the statistics presented above.

Figure 3.9 shows histograms of unfiltered, filtered and compensated power for Case 1 data with $P_{\text{unfilt}}> -25 \text{ dBX}$ and $|V_{\text{unfilt}}| < 3 \text{ m s}^{-1}$. The clutter filter bias is clearly seen from Figs. 3.9a and 3.9b. The shape of the histogram for the compensation results (Fig. 3.9c) is slightly different than the unfiltered data (Figs 3.9a), however the means are nearly equal (see Table 3.5).
3.5 Discussion

The reflectivity compensation method is effective in removing clutter filter reflectivity and radial velocity biases. Removing the bias should yield significant improvements in the radar-estimated precipitation rates. The uncertainty of the power estimates is reduced in precipitation that has a near-zero radial velocity after reflectivity compensation is applied and when compared to the filtered data. Removing radial velocity bias may improve numerical weather prediction model initialization, as well as the results from WSR-88D algorithms that use Doppler data as input.

It was shown that the WSR-88D quantization of the power and Doppler fields and the degradation of the resolution of power does not preclude the reflectivity/velocity compensation method from removing clutter filter biases. Therefore, the method is valid for use on current WSR-88D output. The impact of separate scans for the Doppler and power fields remains to be seen. However, it seems reasonable to expect that separate scans will have a statistically random effect on the method and only slightly impact the average bias of the compensation results. The variance of the compensated power estimates will likely increase.

3.6 Recommendations for FY-01

For FY-01, the evaluation and refinement of the compensation algorithm will continue within the Python Environment for Radar Processing (PERP) that is currently under development. The PERP will allow examination of the algorithm performance within a wider variety of weather conditions than has been previously possible. Using PERP, the method will be implemented on the NCAR S-Pol radar during the IMPROVE field program on the coast of Washington state during the winter of 2001 (Sections 2.4.3 and 4.0). Real-time analysis of the reflectivity compensation method will be constructive for refining the technique despite the lack of verification data. In real-time, the PERP will allow quantization of the S-Pol data to resemble the WSR-88D data resolution as closely as possible.

In post-analysis, repeating the experiments using separate Doppler and power scans will be performed on the S-Pol data from IMPROVE. The data are available and the software
should be straightforward to modify.

A five pole elliptic filter has been designed using WSR-88D specifications with Matlab’s signal processing tool and is ready to apply to the data presented in this report. This is an improvement over the simulated filter used in this study because it more closely resembles WSR-88D processing. Also, the simulated filter was constructed in the spectral domain using 64 pulses from the radar, resulting in low resolution when the Nyquist interval was large (high PRF). The low resolution clutter filter creates errors in the specification of the passband and stopband edge velocities. However, the results presented here remain valid because the simulated filters used to generate the look-up tables are always consistent with the filters used on the data. This is also true for cases with the time domain elliptic filters.

3.7 References


Sirmans, D., 1992: Clutter filtering in the WSR-88D, NWS/OSF, Norman, OK.
4.0 Instrumentation and Diagnostic Techniques

In this section, the tasks discussed are those completed as part of the Instrumentation and Diagnostic Techniques for the NEXRAD Data Quality Optimization. For this fiscal year, three main tasks were accomplished: further development and refinement of the Python Environment for Radar Processing (PERP), analysis of the Archive 1 data taken during the Oklahoma tornado outbreak of 3 May 1999, and investigation of digital IF receivers for a future WSR-88D upgrade.

4.1 Overview of the Python Environment for Radar Processing

The Python Environment for Radar Processing (PERP) is a set of processing modules that implement an A1 Processing Platform (A1PP) and the AP Clutter Mitigation Scheme (Section 1.0). The A1PP processes Archive 1 (A1) time series data into the Archive 2 (A2) base data (reflectivity, radial velocity and spectrum width). The AP Clutter Mitigation Scheme consists of the Radar Echo Classifier (REC) (Section 2.0), the Reflectivity Compensation Scheme (Section 3.0), ground clutter filtering control, and tracking of the AP clutter regions. The AP Clutter Mitigation Scheme is not fully implemented within the PERP but current capabilities include processing the three algorithms of the REC and the Reflectivity Compensation Scheme. The PERP runs in a batch, post-analysis mode or in a real-time mode. Clutter tracking will be implemented during FY-01. Current capabilities include the application of a clutter filter to the A1 data stream using a clutter control map produced by the AP Detection Algorithm.

4.1.1 Design of the PERP

The A1PP ingests Archive 1 data from netCDF files. The netCDF files are produced from time-series data recorded on WSR-88D radars and on NCAR's S-Pol radar. Using the standard pulse-pair algorithm and 1 of ‘N’ standard clutter filters, the A1PP produces Archive 2 (base data) products of reflectivity (Z), radial velocity (V), and spectrum width (W). It produces filtered and unfiltered products simultaneously, emulating the capabilities of the Open RDA. The availability of base data computed from both unprocessed A1 and filtered A1 significantly improves the ability of the Clutter Filter
Control Algorithm to determine when AP clutter dissipates, allowing clutter filters to be disabled appropriately. Base data are produced in a form that can be processed by the Radar Echo Classifier. The A1PP accepts a clutter map that specifies which clutter filter is to be applied for a particular region of gates. Figure 4.1 shows a high level view of the data flow between the A1 Processing Platform and the AP Clutter Mitigation Scheme. Figure 4.2 shows a detailed view of the AP Clutter Mitigation Scheme.

4.1.3. Implementation

Numeric Python was chosen (VanAndel, 2000) as the platform for implementation of the A1 Processing Platform and the AP Clutter Mitigation Scheme because it provides an efficient array processing environment, similar to MATLAB or IDL, but uses a general purpose programming language that can be used for scripting, building GUIs, and systems programming tasks. Using Numeric Python makes it easier to develop and debug our algorithms, since it is an interpreted language that does not require the compile and link phases needed when using a compiled language. In addition, Numeric Python allows interactive examination of the data and plotting of selected values for development and verification of our algorithms.

4.1.3. Brief Description of FY-99 work

The pulse-pair algorithm and the clutter filters were coded and tested. The AP Detection Algorithm within the Radar Echo Classifier was coded and tested. An existing netCDF package was used to read time-series data. As output, the A2 data files were written to
Figure 4.2. Detailed schematic of the AP Clutter Mitigation Scheme.

DORADE format sweep files, that are used by the SOLO display program and PERP.

4.1.4. Review of FY-00 Work

The development and real-time implementation of the PERP is ongoing. Additional features were added this year to greatly increase its functionality. As discussed in Section 2.4, the PERP ran the Radar Echo Classifier (REC) in real-time at the STEPS field program that was held in eastern Colorado during July 2000 (Section 2.4.2). The three REC algorithms were run and output placed onto a World Wide Web page that had movie loop capability. The next real-time operations of the PERP will be at the
IMPROVE field program to be held in Washington on the Pacific coast during January-February 2001 (Section 2.4.3). For the IMPROVE operations with S-Pol, the Reflectivity Compensation Algorithm has been implemented within PERP. The output from the Precipitation Detection Algorithm (PDA) and the AP Detection Algorithm (APDA) are used to determine where and when the reflectivity values within precipitation will be compensated to correct the clutter-filter-induced. Further, quantization of the S-Pol base data fields is an optional task that has been implemented within PERP to simulate the data resolution of the WSR-88D. The S-Pol collects data using a 0.15 km gate spacing while the WSR-88D uses a 1 km gate spacing for reflectivity and 0.25 km gate spacing for radial velocity. Reflectivity data will be quantized over a 1.05 km distance by assigning the maximum value of the 7 gates that are at 0.15 km resolution. The radial velocity data will be averaged over 2 gates for a spatial resolution of 0.3 km.

As discussed in Section 2.6, new feature fields were added to the feature generator of PERP. These new features included the median calculation and the reflectivity variables of SPIN and SIGN.

To evaluate algorithm performance of the REC, a statistical analysis and display package was added to PERP and is discussed in Section 2.4.1. Examples of its output are shown throughout Section 2.8. The statistical indices used are the Critical Success Index (CSI), the Heidke Skill Score (HSS), the Probability of Detection (POD), the False Alarm Ratio (FAR), and the Percent Correct. Their calculation is based on a 2x2 contingency table.

4.2. Analysis of the Oklahoma Tornado Data

Archive 1 data were collected at the Norman, OK, WSR-88D (KCRI) by Dr. Rodger Brown, NSSL, during the tornadic outbreak of 3 May 1999. To examine the effect of increasing the spatial resolution of the WSR-88D base data, the data were processed through the A1PP and Archive 2 base data files written (Fig. 4.3). In particular, the data were processed with 0.5 and 1.0 degree azimuth spacing and with reflectivity data at 0.25 km gate spacing. Current WSR-88D capabilities are 1.0 km gate spacing for reflectivity and 0.25 gate spacing for radial velocity, at 1.0 degree azimuth spacing. This data set will be used to examine NSSL algorithm performance with improved data resolution.
Figure 4.3. Example showing the reprocessed 3 May 1999 Oklahoma tornadic data. The current resolution of the a) reflectivity (dBZ) field at 1 km gate spacing and the b) radial velocity ($\text{m s}^{-1}$) field at 0.25 km gate spacing. One degree azimuthal spacing is used. In c) the reflectivity field gate spacing is decreased to 0.25 km to match the d) radial velocity field. In e) and f), both the reflectivity and radial velocity use a 0.5 degree azimuthal spacing and 0.25 km gate spacing. Different software with different color tables was used to generate a) and b) when compared to c) through e). Also, the data in c) through e) have the radial velocity sign incorrect and dealiasing of the data is needed. This figure was provided by the courtesy of Dr. Rodger Brown, NSSL.
4.3. Digital IF Receiver Assistance

NCAR assisted OSF engineering staff in evaluating several Digital IF receivers for future replacement of the WSR-88D analog receivers. These analog receivers have exceptionally high performance, with a dynamic range of about 90 dB and phase noise over 55 dB below the carrier. A replacement digital receiver will need careful design to match this performance standard.

OSF and NCAR staff reviewed several digital receiver options including commercial units available from Sigmet and Lassen and other systems designed by NCAR and RadTech. After the Technical Interchange Meeting (TIM) in March 2000 the technical staff visited the CSU CHILL radar to discuss their experience with the Lassen digital receiver. OSF staff also purchased a Sigmet RxNet-7 and have installed it on KOUN for further testing.

4.4. Other Tasks

A paper describing Numeric Python was written and presented (VanAndel, 2000) at the 8th International Python Conference on January 24-27th, 2000 and was held in Arlington, Virginia.

4.5. Recommendations for FY-01

The recommendations for development of the PERP and the A1PP for FY-01 are discussed in Section 2.12.

4.6. References

5.0 Other Installations of the AP Detection Algorithm

The AP Detection Algorithm (APDA) has been installed at the Research Applications Program (RAP) at NCAR within the domain of the thunderstorm Auto-Nowcaster (Roberts et al., 1999) under separate funding. This work is reported to the OSF for informational purposes only.

The Auto-Nowcaster produces time and space specific forecasts of the location and intensity of convective weather on time-scales of 30-60 minutes. It uses a variety of radar data as input, including the WSR-88D. While plans for implementing the AP Detection Algorithm at the Sydney Summer Olympics did not materialize as reported in the FY-99 Annual Report (see Section 5.2 of that report), the algorithm is installed within the Auto-Nowcaster framework and is available for use in future field experiments.

Figure 5.1 shows an example of WSR-88D data taken from the Memphis, TN WSR-88D (KNQA) on 6 July 1997 at 04:31 UTC. Using the base data fields of reflectivity (Fig. 5.1a), radial velocity (Fig. 5.1b) and spectrum width (not shown), the FY-99 version of the APDA was run. Those radar gates that are determined to contain ground clutter contamination are deleted from the base data of all fields. Figure 5.1c shows the remaining reflectivity gates after subtraction of those gates containing clutter. The quality-improved base data fields are then input into the fuzzy-logic algorithms that comprise the Auto-Nowcaster.

The FY-99S version of the APDA will be updated by RAP to the FY-00 version after the SPIN and SIGN variables are added.

5.1 References

Figure 5.1. An example of the AP Detection Algorithm is shown after running at NCAR/RAP as part of the Auto-Nowcaster. Data were taken on 6 July 1997 at 04:31 UTC at the Memphis, TN WSR-88D (KNQA). Fields shown include the a) original reflectivity (dBZ) with AP clutter contamination, the b) original radial velocity field (m s$^{-1}$), and c) the reflectivity field with the gates containing AP clutter removed.
Appendix A. Kessinger and VanAndel 17th IIPS Paper
Appendix B. Ellis 17th IIPS Paper
Appendix C. Poster for the American Geophysical Union Conference

This poster was presented at the Spring Meeting of the American Geophysical Union held in Washington, D.C., from 30 May to 3 June 2000. The Abstract follows.

**Evaluation of Various Radar Data Quality Control Algorithms Based on Accumulated Radar Rainfall Statistics**

The primary function of the TRMM Ground Validation (GV) Program is to create GV rainfall products that provide basic validation of satellite-derived precipitation measurements for select primary sites. A fundamental and extremely important step in creating high-quality GV products is radar data quality control. Quality control (QC) processing of TRMM GV radar data is based on some automated procedures, but the current QC algorithm is not fully operational and requires significant human interaction to assure satisfactory results. Moreover, the TRMM GV QC algorithm, even with continuous manual tuning, still can not completely remove all types of spurious echoes.

In an attempt to improve the current operational radar data QC procedures of the TRMM GV effort, an intercomparison of several QC algorithms has been conducted. This presentation will demonstrate how various radar data QC algorithms affect accumulated radar rainfall products. In all, six different QC algorithms will be applied to two months of WSR-88D radar data from Melbourne, Florida. Daily, five-day, and monthly accumulated radar rainfall maps will be produced for each quality-controlled data set. The QC algorithms will be evaluated and compared based on their ability to remove spurious echoes without removing significant precipitation. Strengths and weaknesses of each algorithm will be assessed based on their ability to mitigate both erroneous additions and reductions in rainfall accumulation from spurious echo contamination and true precipitation removal, respectively. Contamination from individual spurious echo categories will be quantified to further diagnose the abilities of each radar QC algorithm. Finally, a cost-benefit analysis will be conducted to determine if a more automated QC algorithm is a viable alternative to the current, labor-intensive, QC algorithm employed by TRMM GV.
Appendix D. Poster Presented at the TRMM Science Meeting

This poster was presented at the TRMM U.S. Science Team Meeting in Greenbelt, Maryland from 30 October - 2 November 2000. This poster is a continuation of the work presented at the AGU Conference and included in Appendix A.