Ground Clutter Mitigation for Weather Radars Using the Autocorrelation Spectral Density

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ABSTRACT

Radar returns from the ground, known as ground clutter, can contaminate weather signals, often resulting in severely biased meteorological estimates. If not removed, these contaminants may artificially inflate quantitative precipitation estimates and obscure polarimetric and Doppler signatures of weather. A ground-clutter filter is typically employed to mitigate this contamination and provide less biased meteorological-variable estimates. This paper introduces a novel adaptive filter based on the autocorrelation spectral density, which is capable of mitigating the adverse effects of ground clutter without unnecessarily degrading the quality of the meteorological data. The so-called Clutter Environment Analysis using Adaptive Processing (CLEAN-AP) filter adjusts its suppression characteristics in real time to match dynamic atmospheric environments and meets Next Generation Weather Radar (NEXRAD) clutter-suppression requirements.

1. Introduction

Radar returns from the ground (known as ground clutter) can greatly affect the performance of weather radars by contaminating weather signals, introducing biases in the meteorological variables, and potentially impeding the recognition of weather phenomena (Doviak and Zrnić 1993). Left untreated, ground-clutter contamination leads to biases in estimates of the spectral moments and the polarimetric variables (e.g., Friedrich et al. 2009). For example, under strong contamination conditions, reflectivity estimates are artificially inflated and Doppler velocities and spectrum widths are shifted toward zero. If not removed, these biases could propagate to algorithms and models that rely on radar data (e.g., Chrisman et al. 1994; Fornasiero et al. 2005).

Ground-clutter filters (GCF) are typically employed to mitigate the negative effects of returns from the ground, which are characterized by near-zero Doppler velocities and narrow spectrum widths (Sirmans 1987, 1992). An effective GCF suppresses most of the ground clutter signal while retaining most of the weather signal, a task that is more suitably accomplished at the signal-processing level, that is, by operating on the received complex voltages [also referred to as the in-phase and quadrature (I and Q) time series data]. Processing limitations of early pulsed Doppler weather radars led to the use of simple, nonrecursive time-domain filters (e.g., Sirmans and Dooley 1980). But as radar signal processors became more powerful, complex techniques ranging from recursive (e.g., Hamidi and Zrnić 1981) and regression filters (e.g., Torres and Zrnić 1999) to adaptive frequency-domain filters (e.g., Passarelli et al. 1981) have become feasible for implementation in operational systems. The reader is referred to Hubbert et al. (2009) and Moisseev and Chandrasekar (2009) for excellent literature reviews on ground-clutter filters for weather radars.

Designing a filter that achieves the required ground clutter suppression under operational conditions is only one side of the problem. The other side consists of devising an effective mechanism to selectively apply the filter only when it is needed. This is important because weather signals may exhibit similar spectral characteristics as ground clutter signals, and also because the ground clutter environment can quickly change over time because of varying anomalous propagation (AP) conditions (Pamment and Conway 1998). Thus, the mitigation of ground-clutter contamination can be more effective if the degree of ground clutter contamination...
(or lack thereof) is dynamically recognized and a suitable filter (or no filter) is adaptively applied.

On the Weather Surveillance Radar-1988 Doppler (WSR-88D), ground clutter mitigation was initially accomplished with a bank of time-domain, five-pole elliptic filters and a static clutter map that controlled the degree of suppression (none, low, medium, or high) at every radar resolution volume (Sirmans 1992; Chrisman et al. 1994). While effective at suppressing contamination from ground clutter returns, this mitigation scheme only allowed for adaptation to the varying clutter environment when the maps were augmented with real-time input from radar operators or entirely recreated on a seasonal basis. Improvements in this area were made feasible only after the upgrade of the legacy signal processor as part of the Open Radar Data Acquisition (ORDA) project (Crum et al. 1998). The Gaussian model adaptive processing (GMAP) filter (Siggia and Passarelli 2004) replaced the legacy bank of elliptic filters and included the ability to adapt its suppression to the clutter environment in real time, which resulted in overall improved performance (Ice et al. 2004). Thus, the legacy static map was simplified to a (still static) binary map that controlled the application (or not) of the GMAP filter. In a recent upgrade of the ORDA, the static clutter map was complemented by the clutter mitigation decision (CMD) algorithm (Hubbert et al. 2009). CMD uses the so-called clutter phase alignment and various spatial features in a fuzzy logic scheme to perform automatic clutter detection in real time and thus control the application of the GMAP filter without operator intervention (Ice et al. 2009). Although significant improvements were realized with the implementation of CMD and GMAP on the WSR-88D, more can be achieved by integrating filtering and its control into a single algorithm. Bachmann et al. (2008) had one of the earliest successes in this regard, and their work has served as inspiration to extend the use of spectral phase information to improve ground clutter mitigation for weather radars.

In general, techniques that operate on $I$ and $Q$ samples from a single radar-resolution volume are better suited for integration with other signal-processing functions and operational implementation. However, one of the drawbacks of this approach is that, in the absence of additional information, weather signals with near-zero Doppler velocities and narrow spectrum widths may be incorrectly attenuated because they exhibit characteristics similar to those of ground clutter returns. The use of information from neighboring resolution volumes (e.g., spatial textures) has been shown to add skill in the discrimination between weather signals in the so-called zero-velocity isodop (i.e., echoes with zero Doppler velocity) and those from ground clutter (e.g., Fabry and Gadoury 2009). Nevertheless, detection and filtering functions are most effective when integrated into a single algorithm (e.g., Moisseev and Chandrasekar 2009).

The technique described in this paper is referred to as the Clutter Environment Analysis using Adaptive Processing (CLEAN-AP$^1$) filter. It operates on $I$ and $Q$ samples from a single radar-resolution volume and integrates both aspects of the ground clutter mitigation process: selective filter application and effective clutter suppression. At the core of CLEAN-AP is the autocorrelation spectral density (ASD) introduced by Warde and Torres (2014): an extension of the classical power spectral density (PSD) that includes spectral phase information. CLEAN-AP combines the use of adaptive data windows and the argument of the lag-1 ASD to provide a suitable compromise between clutter suppression and the quality of the meteorological variables obtained after filtering. In this paper, simulations and real data recorded from two operational WSR-88D radars are used to evaluate and illustrate the performance of the CLEAN-AP filter, which is shown to adapt its suppression to the detected clutter environment. As a result, it meets the ground-clutter-suppression requirements for the WSR-88D (NEXRAD Radar Operations Center 1996). That is, it provides effective suppression of ground clutter returns up to (at least) 50 dB stronger than the weather returns with small biases in the resulting meteorological variables (except, as allowed in the requirements, for weather signals with near-zero Doppler velocities and very narrow spectrum widths).

The rest of the paper is structured as follows. The CLEAN-AP filter is described in section 2 and its performance is analyzed using simulations in section 3. In section 4, the technique is applied to radar observations from the KTLX radar in Twin Lakes, Oklahoma (prior to its upgrade to dual polarization), and the KVNX radar at Vance Air Force Base in Enid, Oklahoma (after its dual-polarization upgrade). Section 5 ends with a short summary and plans for future work.

2. The CLEAN-AP filter

The CLEAN-AP filter operates on a single-resolution-volume, single-dwell set received complex voltages, $V(m)$ ($0 \leq m < M$). Here, $m$ indexes sample time at pulse repetition time (PRT) increments $T_{p}$ and $M$ is the number of samples per dwell (the range-time index is irrelevant and omitted herein). The CLEAN-AP filter is equally

\footnote{CLEAN-AP ©2009 Board of Regents of the University of Oklahoma.}
suited for single- and dual-polarization weather radars, and variations in processing between these implementations are identified in the algorithm description that follows. In a nutshell, the CLEAN-AP filter consists of four steps: data window selection, lag-1 ASD computation, clutter-extent determination, and filtering. Whereas the processing path on a single-polarization implementation is straightforward, in a dual-polarization implementation the choice is between the simpler master–slave channel configuration and the combined-channel configuration. In the master–slave channel configuration, all adaptation is based on information from only one of the polarimetric channels (typically the horizontal one, as done on the WSR-88D). Conversely, in the combined-channel configuration, adaptation is based on information from both channels, which could be more effective in cases where ground clutter and weather returns exhibit markedly different polarimetric characteristics. Herein, the dual-polarimetric master–slave channel configuration is chosen for the simulations and real-data processing—still, both options are described for the adaptive steps of the algorithm in this section. For dual-polarization radars, only the simultaneous (or hybrid) transmission mode (Bringi and Chandrasekar 2001) is considered; the reader is referred to Warde and Torres (2013) for an extension of the CLEAN-AP filter to dual-polarization radars employing the alternating transmission mode.

a. Data window selection

A data window should achieve a suitable compromise between clutter suppression and the variance of meteorological-variable estimates after filtering. That is, more tapered windows lead to larger variance of estimates but reduce the spectral leakage from strong ground clutter signals and result in improved ground clutter mitigation. The opposite holds for less tapered windows; thus, the degree of tapering may be tailored to the dynamic range of the signals under analysis. To estimate the required amount of tapering, the direct current (DC) power (a proxy for clutter power) is compared to the noise power per frequency bin as

\[
\text{CNR} = 10 \log_{10} \left( \frac{1}{NM} \sum_{m=0}^{M-1} V(m)^2 \right),
\]

where the \( N \) is the system noise power on single-polarimetric radars or the channel-specific noise power on dual-polarimetric radars. It should be noted that this quantity is only a rough estimate of the actual clutter-to-noise ratio (CNR). However, its use is confined to the window selection process, for which it is adequate.

The “best” data window is the least tapered window that has sidelobes below \( \text{CNR} \) (on a dual-polarization implementation, this is computed for the master channel in a master–slave configuration or as the maximum between the two channels for a combined-channel configuration). Whereas such a data window could be found using optimization techniques (e.g., Adams 1991), it is simpler (and not significantly detrimental) to choose between data windows that are readily available in real-time signal-processing environments. For this implementation, the data window is adaptively selected between the rectangular, von Hann, Blackman, and Blackman–Nuttall windows, which have mainlobe-to-maximum-sidelobe levels of \(-13, -32, -58, \) and \(-98 \) db, respectively (Harris 1978; Nuttall 1981). Thus, the rectangular window is selected for \( \text{CNR} \) values less than \( 13 \) db, the von Hann window between 13 and 32 db, the Blackman window between 32 and 58 db, and the Blackman–Nuttall window for values above 58 db. Finally, all data windows are normalized to be power preserving; thus, no correction is needed for the quantities computed from the windowed \( I \) and \( Q \) samples.

Figure 1 shows histograms (and their means) of data window selection for a clutter-contaminated weather signal as a function of the clutter-to-signal ratio (CSR). The y axis corresponds to the different windows available for selection, and the gray intensities represent the frequency of selection as a percentage of the total number of simulated realizations. As expected, the selected window becomes progressively more tapered as the clutter...
conjugation and where the superscript asterisk (*) denotes complex side of (2) and of PSDs from with the ASD, the PSD can be computed as the average requires two ASDs, one for each channel. For consistency otherwise, using the combined-channel configuration re-
configuration, only the master–channel ASD is computed; implementation using the master–slave channel con-

\begin{equation}
S_i(k) = F_0^*(k)F_i(k), \quad 0 \leq k < M - 1,
\end{equation}

where the superscript asterisk (*) denotes complex conjugation and

\begin{equation}
F_i(k) = \frac{1}{M - 1} \sum_{m=0}^{M-2} d(m)V(m + l)e^{-j2\pi mk(i(M-1))},
\end{equation}

where \(l = 0, 1\) for each of the factors on the right-hand side of (2) and \(d\) is the \((M - 1)\)-sample data window obtained in the previous step. In a dual-polarization implementation using the master–slave channel configura-
tion, only the master–channel ASD is computed; otherwise, using the combined-channel configuration re-
quires two ASDs, one for each channel. For consistency with the ASD, the PSD can be computed as the average of PSDs from \(F_0\) and \(F_1\) (i.e., Welch’s method). This en-
sures that both spectral representations are on the same frequency axis and are derived from all available samples.

c. Ground-clutter extent determination

In this step, spectral leakage in the argument of the lag-1 ASD is used to identify the spectral coefficients around zero Doppler velocity with significant ground-clutter contamination. As described by Warde and Torres (2014), the argument of the ASD of a narrow-
band signal (such as ground clutter returns) locally “flattens” (i.e., there is a bias compared to the ideal or expected argument) around the magnitude spectral peak due to the large power gradient. On the other hand, the argument of the ASD of a wideband signal appears nearly unbiased thanks to the relatively small power gradient.

FIG. 2. (top) Magnitude and (bottom) argument of the ideal ground clutter lag-1 ASD and for the clutter-model lag-1 ASD using the four available data windows (rectangular, von Hann, Blackman, and Blackman–Nuttall). The spectrum width of ground clutter is 0.4 m s\(^{-1}\), the Nyquist velocity is 28 m s\(^{-1}\), and \(M = 66\). The maximum arguments of the clutter-model lag-1 ASD are 0.06, 0.10, 0.14, and 0.19 rad for the rectangular, von Hann, Blackman, and Blackman–Nuttall windows, respectively.

Biases in the argument of the lag-1 ASD due to the spectral leakage of ground clutter signals can be predicted by modeling the argument of the lag-1 ASD for a ground clutter return. The so-called clutter model is based on an ideal Gaussian spectrum with zero mean Doppler velocity and an adjustable spectrum width, which controls the filter’s maximum suppression. For this work, the spectrum width of the clutter model is set to 0.4 m s\(^{-1}\), which matches the value used by the GMAP filter on the WSR-88D. The clutter-model lag-1 ASD is generated for each data window by convolving a finely sampled, “ideal” ground clutter lag-1 ASD (the magni-
tude is Gaussian with zero mean Doppler velocity and 0.4 m s\(^{-1}\) spectrum width, and the argument is linear with unit slope) with the power spectral density of the \((M - 1)\)-sample data window (zero padded to the same number of samples as the ideal clutter ASD, which is 512 in our case). Figure 2 shows the clutter-model lag-1 ASD for the four possible data windows and the ideal ground clutter lag-1 ASD. In practice, the clutter-model lag-1 ASD can be precomputed for given values of \(M\) and Nyquist velocity, and the maximum arguments (one value for each data window) can be stored to be used in the real-time determination of clutter extent as described next.

A spectral coefficient is identified as clutter contami-
nated if the corresponding lag-1 ASD coefficient has a magnitude above the spectral noise floor and an ab-
solute argument less than the maximum value predicted.
by the clutter model. For a more robust determination, the argument of the ASD is previously smoothed with a running median filter to minimize the impact of statistical fluctuations (a three-point filter was empirically selected based on simulation results). In addition, up to two ASD coefficients that do not meet the argument requirement are allowed inside (but not at the end) of each half of the clutter extent when partitioned into positive and negative Doppler velocities. In a dual-polarization implementation using the combined-channel configuration, both ASDs are subjected to this process, and the clutter extent is defined as the maximum between the two channels.

Figure 3 shows an example of clutter-extent determination using the argument of the lag-1 ASD from time series data collected with the KOUN radar. Spectral coefficients identified as having clutter contamination are indicated with circles over the (top) magnitude and (bottom) argument of the unfiltered lag-1 ASD. Only 15 of the 65 total spectral coefficients are shown ($M = 66$). The (bottom) plot also shows the maximum and minimum values expected in the argument of the ASD of the clutter model using the Blackman window (dotted lines) and the ideal argument of the ASD for a very large number of samples (gray line).

### Filtering

Having identified the spectral coefficients with significant ground-clutter contamination in the lag-1 ASD, the next step is to remove the contamination from the corresponding coefficients in the other spectral densities. Using the ASD as a basis for this makes sense in a single-polarization implementation because, in the mean, the magnitude of the ASD equals the PSD (Warde and Torres 2014), so the clutter extent is the same on both spectral representations. However, in a dual-polarization implementation, the horizontal- and vertical-channel PSDs and the ASDs and the cross-spectral density (CSD) may not have the same distribution of powers as a function of Doppler velocity. Thus, in a master–slave configuration, using the clutter extent as determined from the master-channel ASD may lead to inadequate suppression for the slave channel. However, this is an issue only in radar volumes where the polarimetric characteristics of ground clutter returns are markedly different from those of weather returns (e.g., $Z_{DR}$ of clutter returns is negative and that of weather returns is positive). In principle, a combined-channel configuration in which the clutter extent is determined using information from both polarimetric...
Figure 5 illustrates the results of the complete CLEAN-AP process and shows the magnitude and argument of the unfiltered (gray) and filtered (black) lag-1 ASD for data collected with the KOUN radar in Norman, Oklahoma, on 19 March 2006. Data correspond to three different resolution volumes (at different ranges) for the same antenna position: one with ground clutter (left), one with hydrometeors (middle), and one with a mix of ground clutter and hydrometeors (right). For all cases, \( M = 66 \) and the Nyquist velocity \( v_N = 28 \text{ m s}^{-1} \). The Blackman–Nuttall window was selected for the clutter-only case, the rectangular window for the weather-only case, and the Blackman window for the weather-and-clutter case. The number of spectral coefficients identified as having clutter contamination and the amount of clutter suppression are listed for each case. In the weather-only case, only the zero-velocity coefficient is identified as having clutter contamination and no filtering is applied (NW = 0).

Filtering is done in two different ways depending on which meteorological variable is to be estimated from the filtered spectra. The spectral moments are typically derived from estimates of the autocorrelation function \( R \) at a few small lags (Doviak and Zrnić 1993); without loss of generality, we assume that only the first two lags, \( R(0) \) and \( R(1) \), are required. In this case, the coefficients identified as clutter contaminated are removed from \( S \) (the PSD) and \( S_1 \) (the lag-1 ASD), which is straightforward because the two spectral representations are on the same frequency axis. Then, a linear interpolation (independently applied to the magnitudes of the PSD and ASD in logarithmic units and to the argument of the ASD) is used to compensate for the potential weather-signal loss around zero Doppler velocity. Despite its apparent lack of sophistication, this linear interpolation scheme has an overall performance similar to that of the GMAP’s iterative Gaussian interpolation scheme, so it was preferred because of its computational simplicity.
Because correlations and spectral densities (the PSD and the ASD) are Fourier transform pairs, $R(0)$ and $R(1)$ can be computed from the filtered PSD and ASD, $\tilde{S}$ and $\tilde{S}_1$, as

$$R(0) = \sum_{k=0}^{M-2} \tilde{S}(k)$$  \hspace{1cm} (4)

and

$$R(1) = \sum_{k=0}^{M-2} \tilde{S}_1(k),$$  \hspace{1cm} (5)

respectively. Note that $R(0)$ could also be computed as the sum of the magnitudes of the filtered lag-1 ASD. Other spectral-moment estimators based on higher autocorrelation lags (e.g., the hybrid spectrum width estimator described by Meymaris et al. 2009) can be similarly computed by using the ASD at higher lags, which increases the computational complexity, or from the lag-1 ASD as

$$R(1 + l) = \sum_{k=0}^{M-2} \tilde{S}_1(k)e^{[2\pi kl/(M-1)]}, \hspace{1cm} l > 0,$$  \hspace{1cm} (6)

which does not significantly increase the computational complexity but requires bias corrections as described by Torres et al. (2007). As implied earlier, in this work we use the classical spectrum width estimator based on the ratio $R(0)/R(1)$ (Doviak and Zrnić 1993).

The polarimetric variables are typically derived from estimates of lag-zero autocorrelations, $R_h(0)$ and $R_v(0)$, and cross correlation, $R_{hv}(0)$ (Bringi and Chandrasekar 2001). In this case, the coefficients identified as clutter contaminated are simply removed (zeroed out) from $S_h$, $S_v$ (the PSDs computed from $V_h$ and $V_v$, respectively), and $S_{hv}$ (the CSD computed from $V_h$ and $V_v$). A spectral reconstruction to mitigate potential signal loss around zero Doppler velocity is not needed nor desired in this case, as it would bias the polarimetric variable estimates (Zrnić et al. 2008). Finally, $R_h(0)$, $R_v(0)$, and $R_{hv}(0)$ are computed as the sums of filtered densities $\tilde{S}_h$, $\tilde{S}_v$, and $\tilde{S}_{hv}$, respectively [cf. (4)], and other estimators based on higher correlation lags (e.g., Lei et al. 2012) can be computed using expressions analogous to (6).

3. Simulations

In this section, the performance of the CLEAN-AP filter under a wide variety of conditions is characterized using simulations. Instead of comparing to one of the many existing ground-clutter filtering techniques, we will show that the CLEAN-AP filter meets (and in most cases exceeds) the set of WSR-88D operational requirements for ground-clutter suppression (NEXRAD Radar Operations Center 1996). WSR-88D clutter-suppression requirements are defined for a clutter-contaminated weather signal model in which the weather signal has an SNR of 20 dB and a spectrum width of 4 m s$^{-1}$ and the ground clutter signal has a Doppler velocity of 0 m s$^{-1}$. Not specified in this model is the spectrum width of the ground clutter signal, which we set to 0.28 m s$^{-1}$ as in previous similar analyses (e.g., Ice et al. 2004; Sirmans 1992). Also not specified are the polarimetric characteristics of weather and clutter signals in the model. In fact, WSR-88D clutter-suppression requirements are only given in the context of single polarization, where the expectation is that the performance obtained from naturally extending the GCF to the polarimetric variables is acceptable. As described in the previous section, the CLEAN-AP filter is extended to dual-polarization radars in the same manner that the GMAP filter was extended for the WSR-88D (Zrnić et al. 2008). Thus, the performance of the CLEAN-AP filter will be quantitatively assessed using only the available single-polarization requirements. Nevertheless, qualitative performance of CLEAN-AP will be shown using data from both single- and dual-polarization radars in section 4.

For each set of model parameters, 1000 realizations of time series data are simulated using the procedure described by Zrnić (1975) with 64 samples, a PRT of 1 ms, and a radar frequency of 2850 MHz. Variable model parameters (i.e., those not specified in the requirements) include the weather-signal Doppler velocity and spectrum width, and the CSR. In this analysis, the weather-signal Doppler velocity ($v$) is varied from 0 to 26.3 m s$^{-1}$ in 55 steps of 0.48 m s$^{-1}$, and the spectrum width ($\sigma_v$) is varied a total of 20 steps: from 0.1 to 1 m s$^{-1}$ in steps of 0.1 m s$^{-1}$, from 1 to 4 m s$^{-1}$ in steps of 0.5 m s$^{-1}$, and from 4 to 8 m s$^{-1}$ in steps of 1 m s$^{-1}$. The CSR is varied from −30 to 70 dB in 21 steps of 5 dB.

As dictated by the WSR-88D clutter-suppression requirements, the performance of the CLEAN-AP filter is assessed in terms of suppression and also in terms of biases and standard deviations of reflectivity, Doppler velocity, and spectrum width estimates after filtering. The required clutter suppression, defined as the ratio of unfiltered to filtered powers, is 30 dB for reflectivity estimates and either 20 dB (low suppression), 30 dB (medium suppression), or 50 dB (high suppression) for Doppler velocity and spectrum width estimates. However, clutter suppression for modern filters adapts to the amount of clutter present in the received echoes, so it is not tied to fixed levels. Ideally, clutter suppression should be given by the ratio of the sum of weather- and clutter-signal powers to the weather-signal power; this assumes a clutter-contaminated signal at the input of the filter and...
perfect clutter removal at its output. In practice, it is seldom possible to completely remove the clutter signal without affecting the weather signal, so a clutter suppression of 0 dB (input and output powers are the same) is acceptable for clutter contamination that, if unfiltered, would not induce significant estimate biases. The level of clutter contamination for which this holds is different for each meteorological variable, and the reader is referred to Friedrich et al. (2009) for an analysis of meteorological-estimate biases due to ground-clutter contamination.

Because a GCF induces biases that depend on the velocity and spectrum width of the weather signal, maximum allowable biases are normally specified for weather signals with Doppler velocities in the filter’s passband and different spectrum widths (Sirmans 1992). For the WSR-88D, the filter’s passband is defined as all Doppler velocities outside the interval \((-v_0, v_0)\), where \(v_0\) (the passband edge velocity) should be no larger than 2, 3, and 4 m s\(^{-1}\) for clutter-suppression levels of 20, 30, and 50 dB, respectively. For the CLEAN-AP filter, the passband is defined by the spectral extent of ground clutter (or the filter’s notch width). For a clutter-free condition (i.e., a CSR of \(-30\) dB in the model), WSR-88D clutter-suppression requirements specify that application of the filter should result in maximum reflectivity biases no larger than 10, 2, and 1 dB (in absolute value) for all velocities in the passband and for spectrum widths of 1, 2, and larger than 3 m s\(^{-1}\), respectively. Additionally, velocity and spectrum width biases and standard deviations should not exceed 2 m s\(^{-1}\) each for weather signals in the passband. Throughout this analysis and to simplify the validation of requirements, filtered estimate biases and standard deviations are computed with respect to the true simulation parameters. Thus, in addition to the effects of the filtering process, they include any errors inherent to the meteorological-variable estimators. To facilitate the assessment of the filter’s performance, we will draw attention to specific situations where estimator errors dominate the results.

In the presence of ground clutter (interpreted to mean for CSRs above \(-30\) dB), the WSR-88D requirements allow for additional errors due to clutter residue. For reflectivity, the allowed bias is 1 dB for spectrum widths greater than or equal to 4 m s\(^{-1}\) when the output CSR is \(-10\) dB. For velocity and spectrum width, the allowed biases and standard deviations are 1 m s\(^{-1}\) each for a spectrum width of 4 m s\(^{-1}\) and velocity of \(v_0/2\) with output CSRs of \(-11\) and \(-15\) dB, respectively. Although not a requirement, a goal of \(<2\)-dB standard deviation of reflectivity estimates after averaging four 250-m gates in range is also desirable (e.g., Ice et al. 2004). For typical range correlations, this goal means that the standard deviation of nonrange-averaged reflectivity estimates should be below \(-2.74\) dB. The performance of the CLEAN-AP filter is evaluated against these requirements and goals next.

### a. Ground clutter suppression

Figure 6 shows the CLEAN-AP filter clutter suppression (left \(y\) axis) and reflectivity bias (right \(y\) axis) for different CSRs (\(x\) axis), evaluated using the weather-and-clutter model described above. For each CSR value, the average performance of 55 000 realizations is shown (i.e., the 55 weather-signal velocities, each with 1000 realizations, are combined). Note that, in average, the suppression of the CLEAN-AP filter follows the ideal behavior given by \(10\log_{10}[(P_c + P_w)/P_w]\), where the unfiltered power is the sum of clutter- and weather-signal powers, \(P_c + P_w\), and the filtered power is the expected weather-signal power \(P_w\). The CLEAN-AP suppression curve shows that there is no mitigation for CSRs below \(-15\) dB and a one-to-one correspondence (dotted line) for CSRs above 10 dB. Reflectivity estimates after the application of the CLEAN-AP filter (including cases both in the filter’s stopband and passband) exhibit very small negative biases for all CSRs. A more detailed analysis of the filter effects on the bias and standard deviation of spectral-moment estimates as a function of Doppler velocity and spectrum width is provided next.

### b. Biases and standard deviations of spectral-moment estimates

Biases in the meteorological variables after filtering quantify the negative effects that the filter has on the
weather signal. WSR-88D clutter-suppression requirements are written to assess the effects of the filter when the weather signal is not contaminated by ground clutter (the CSR is set to −30 dB in the weather-and-clutter model). In Fig. 7a, the bias of reflectivity estimates is shown for each of the weather-signal spectrum widths (y axis) and velocities (x axis) in the simulated range. The color scale of reflectivity bias (dB) ranges from $<−20$ (maroon) to 0 (white) to 1 (pink). Note that a positive reflectivity bias indicates a situation in which the power at the output of the filter is larger than at its input, which can happen because of the spectral interpolation process. The asterisks in Fig. 7a mark the input, which can happen because of the spectral in-

The standard deviations at the benchmark spectrum widths, larger standard deviations are inherent to the estimator (e.g., Fig. 6.2 of Doviak and Zrnić 1993); however, the increase as the velocity approaches zero is not related to the estimator but to the filtering process. For example, for a spectrum width of 8 m s$^{-1}$, increases in the standard deviation of velocity estimates attributed to the filtering process systematically reduce from a maximum of 0.5 to 0 m s$^{-1}$ for velocities from 0 to $v_c/2$ as compared to corresponding values above $v_c/2$. Using similar comparisons, the increase due to filtering for the standard deviation of velocity estimates can be seen to be less than 1 m s$^{-1}$ except for $\sigma_v < 1$ m s$^{-1}$ and $v < 1.5$ m s$^{-1}$. The standard deviation of velocity estimates at the benchmark is 1.1 m s$^{-1}$, this represents an increase of 0.2 m s$^{-1}$ as compared to 0.9 m s$^{-1}$ at $v_c$. 

Figure 7c shows the bias of spectrum width estimates. As before, an asterisk at a velocity of 2 m s$^{-1}$ and a spectrum width of 4 m s$^{-1}$ marks the benchmark for which filtered spectrum width biases are required to be below 2 m s$^{-1}$. This figure shows that the magnitude of the bias for filtered spectrum width estimates is more than 2 m s$^{-1}$ only for weather-signal spectrum widths below 0.7 m s$^{-1}$ and velocities smaller than 1 m s$^{-1}$ with a maximum of 8.6 m s$^{-1}$ at $v$ and $\sigma_v = 0$ m s$^{-1}$. For other conditions, the spectrum width biases are well below 1 m s$^{-1}$ (light red to light blue) with a bias of $−0.02$ m s$^{-1}$ at the benchmark. Figure 7f shows the standard deviation of spectrum width estimates. Increases in the spectrum width standard deviation for narrow spectrum widths and large spectrum widths are inherent to the estimator (e.g., Fig. 6.6 of Doviak and Zrnić 1993). At a CSR of −30 dB, the standard deviation of spectrum width estimates is below 2 m s$^{-1}$ for $\sigma_v > 0.8$ m s$^{-1}$ and $v > 1$ m s$^{-1}$, and it is 0.46 m s$^{-1}$ at the benchmark.
FIG. 7. (a) Bias of reflectivity estimates (dB) after filtering as a function of the true spectrum width (y axis, m s$^{-1}$) and velocity (x axis, m s$^{-1}$) for the clutter-contaminated signal model with a CSR of −30 dB. Asterisks mark the WSR-88D requirement benchmarks at a velocity of 0 m s$^{-1}$ and spectrum widths of 1, 2, and 3 m s$^{-1}$, where reflectivity biases are required to be <10, 2, and 1 dB, respectively. For each velocity and spectrum width, 1000 realizations of simulated clutter-contaminated weather signals are used with $M = 64$ and $\nu_y = 26.3$ m s$^{-1}$. For the weather signal, the SNR is 20 dB, $\nu$ varies from 0 to $\nu_y$ in 55 steps of 0.48 m s$^{-1}$ for each $\nu_s$ value between 0.1 and 8 m s$^{-1}$. For the clutter signal, $\nu = 0$ m s$^{-1}$ and $\nu_s = 0.28$ m s$^{-1}$. (b) As in (a), but for the standard deviation of reflectivity estimates (dB) after filtering. (c) As in (a), but for the bias of velocity estimates after filtering [color scale (m s$^{-1}$) with negative values indicating a bias toward zero]. An asterisk marks the WSR-88D requirement benchmark at a velocity of 2 m s$^{-1}$ and a spectrum width of 4 m s$^{-1}$ where the velocity bias is required to be <2 m s$^{-1}$. (d) As in (b), but for the standard deviation of velocity estimates (color scale, m s$^{-1}$) after filtering. An asterisk marks the WSR-88D requirement benchmark at a velocity of 2 m s$^{-1}$ and a spectrum width of 4 m s$^{-1}$ where the standard deviation of velocity estimates is required to be <2 m s$^{-1}$. (e) As in (c), but for the bias of spectrum width estimates after filtering (color scale, m s$^{-1}$). (f) As in (d), but for the standard deviation of spectrum width estimates (color scale in m s$^{-1}$) after filtering.
As critical as it is to study the negative effects of the filter to the weather signal when there is no clutter contamination (CSR = −30 dB), the WSR-88D clutter-suppression requirements address the performance of the filter under more demanding clutter-contamination conditions (CSR = 50 dB). For spectrum widths at or greater than 4 m s\(^{-1}\), the reflectivity bias is required to be less than 1 dB. Although not a requirement, one should expect reduced biases in the passband of the filter. From Fig. 4, the mean extent of ground clutter at a CSR of 50 dB is \(0.15\) of the Nyquist co-interval, which can be equated to a passband edge velocity of about \(±4 \text{ m s}^{-1}\) for the simulation parameters used here. The content and layout of Figs. 8a–f is the same as Figs. 7a–f, except that the CSR is 50 dB. Figure 8a shows that, at the passband edge velocity of 4 m s\(^{-1}\) and for spectrum widths of 1, 2, and 3 m s\(^{-1}\), observed reflectivity biases are \(-1.0, -1.7,\) and \(-1.1\) dB, respectively. Note that the magnitude of the bias of reflectivity estimates after filtering stays under 1 dB (very light blue to pink) throughout the Nyquist interval for spectrum widths above 3.0 m s\(^{-1}\) or velocities above 4.4 m s\(^{-1}\), under 2 dB (purple to pink) for spectrum widths above 2.5 m s\(^{-1}\) or velocities > 3.4 m s\(^{-1}\), and under 10 dB (blue-green to pink) for spectrum widths above 1 m s\(^{-1}\) or velocities > 2.5 m s\(^{-1}\). In this case, small positive biases (pink) are less than 1 dB with a maximum of 0.94 dB at \(v = 4.4\) m s\(^{-1}\) and \(σ_v = 0.2\) m s\(^{-1}\); as mentioned before, these are attributed to the spectral interpolation used in the filtering process. In Fig. 8b, the standard deviation of reflectivity estimates is larger than the levels seen in Fig. 7b but the increase is still within the goal of \(-2.74\) dB for spectrum widths above 0.8 m s\(^{-1}\). As in Fig. 7b, Fig. 8b shows artificially reduced standard deviations for spectrum widths in the filter stopband; these are accompanied by large biases (Fig. 8a) and should not be construed as a performance improvement.

The velocity biases observed in Fig. 8c are under 2 m s\(^{-1}\) except for the estimates at \(σ_v = 0.3\) m s\(^{-1}\) and \(v = 2.3\) m s\(^{-1}\) where the observed bias is 2.2 m s\(^{-1}\). At the benchmark of \(σ_v = 4\) m s\(^{-1}\) and \(v = 4\) m s\(^{-1}\), the velocity bias is \(-0.8\) m s\(^{-1}\). In fact, the magnitude of the bias of velocity estimates is less than 1 m s\(^{-1}\) for all velocities in the filter passband and for all spectrum widths above 3 m s\(^{-1}\). In Fig. 8d, the standard deviation of velocity estimates is below 2 m s\(^{-1}\) for all velocities with spectrum widths between 1.5 and 7 m s\(^{-1}\), and is 1.5 m s\(^{-1}\) at the benchmark (\(σ_v = 4\) m s\(^{-1}\) and \(v = 4\) m s\(^{-1}\)). As noted before, inherent to the estimator is an expected increase in the standard deviation of velocity estimates as the spectrum width increases. Using the same analysis as with Fig. 7d, the filter-induced standard deviation increases are \(<2 \text{ m s}^{-1}\) for \(σ_v > 1.0\) m s\(^{-1}\) and \(v > 2.5\) m s\(^{-1}\) and \(<1 \text{ m s}^{-1}\) for \(σ_v > 1.5\) m s\(^{-1}\) and \(v > 2.9\) m s\(^{-1}\) with a 0.45 m s\(^{-1}\) increase at the benchmark.

Seen in Fig. 8e, the magnitude of the biases for filtered spectrum widths are \(<2 \text{ m s}^{-1}\) for \(σ_v > 1\) m s\(^{-1}\) and \(v > 2.4\) m s\(^{-1}\), and \(<1 \text{ m s}^{-1}\) for \(σ_v > 1.5\) m s\(^{-1}\) and \(v > 3.4\) m s\(^{-1}\). At the benchmark (\(σ_v = 4\) m s\(^{-1}\), \(v = 4\) m s\(^{-1}\)), the bias is \(-0.03\) m s\(^{-1}\). In Fig. 8f, the standard deviation of spectrum width estimates is below 2 m s\(^{-1}\) for \(σ_v > 1\) m s\(^{-1}\) or \(v > 2.4\) m s\(^{-1}\), and it is 0.82 m s\(^{-1}\) at the benchmark.

As seen in the statistical analyses using simulations, the performance of the CLEAN-AP filter comfortably meets the WSR-88D operational requirements for ground-clutter suppression, bias, and standard deviation of spectral-moment estimates. Whereas two extreme contamination cases are mainly discussed in this section (no contamination at a CSR of \(-30\) dB and strong contamination at a CSR of 50 dB), the performance of the CLEAN-AP filter was comprehensively evaluated at CSRs ranging from \(-30\) to 70 dB (e.g., see Fig. 6; Torres et al. 2010, 2012). Through this evaluation it was determined that the integrated filter design provides automatic adjustment of clutter suppression while recovering meteorological estimates in all expected operational clutter environments: from no contamination to a CSR of (at least) 50 dB.

4. Application to WSR-88D data

In this section, the performance of the CLEAN-AP filter is assessed using data collected with operational WSR-88D radars. Whereas only limited to the examples shown, qualitative assessments of meteorological-variable fields are used to illustrate that the performance of the CLEAN-AP filter is as expected and in support of the quantitative results presented in the previous sections. The performance of the CLEAN-AP filter with strong (dominant) clutter contamination is assessed by focusing on regions of the filtered fields where the corresponding unfiltered fields clearly exhibit textures and values typical of ground clutter returns (e.g., elevated and spatially inconsistent reflectivities, near-zero Doppler velocities, and narrow spectrum widths for single-polarization data). Supporting the results in Fig. 8, it is expected that the filtered fields in these regions will show smoother textures that are typical of weather returns and values that are consistent with those in neighboring regions with no apparent ground-clutter contamination. To assess the performance of the CLEAN-AP filter for the case of little-to-no ground-clutter contamination, the focus will be on regions of the filtered fields where the corresponding unfiltered fields clearly exhibit textures and values typical of weather returns. Supporting the results in Fig. 7, it is expected that the unfiltered and filtered fields in these regions will be almost identical except perhaps along the zero isodop.
FIG. 8. As in Fig. 7, but for a CSR of 50 dB. In (c),(d), an asterisk marks the WSR-88D requirement benchmark at a velocity of 4 m s$^{-1}$ and a spectrum width of 4 m s$^{-1}$ where the velocity bias is required to be $<2$ m s$^{-1}$ and where the standard deviation of velocity estimates is required to be $<2$ m s$^{-1}$, respectively. In (e),(f) as in (c),(d).
FIG. 9. (left) Unfiltered and (right) filtered PPI displays of (top) reflectivity, (middle) Doppler velocity, and (bottom) spectrum width fields collected with the KTLX radar in Twin Lakes on 27 Oct 2006 at an elevation angle of 0.5°; $M = 18$ and $T_s = 3.107$ ms for reflectivity estimates and $M = 53$ and $T_s = 0.987$ ms ($u_o = 26\text{ m s}^{-1}$) for Doppler velocity and spectrum width estimates.
FIG. 10. (a) As in Fig. 9, but for the KVNX radar at Vance Air Force Base on 8 Mar 2011 at an elevation angle of 0.5°; $M = 17$ and $T_s = 3.107$ ms for reflectivity and polarimetric-variable estimates, and $M = 61$ and $T_s = 0.847$ ms ($\nu_s = 30.6$ m s$^{-1}$) for Doppler velocity and spectrum width estimates. (b) As in (a), but for (top) differential reflectivity, (middle) differential phase, and (bottom) correlation coefficient.
FIG. 10. (Continued)
The CLEAN-AP filter was applied to $I$ and $Q$ samples collected with the KTLX radar in Twin Lakes on 27 October 2006 at an elevation angle of 0.5°; 18 samples per dwell at a PRT of 3.107 ms were processed for reflectivity estimates, and 53 samples per dwell at a PRT of 0.987 ms ($v_a = 26$ m s$^{-1}$) were processed (independently) for Doppler velocity and spectrum width estimates. Range overlaid echoes in the short-PRT data (e.g., purple in Doppler velocity and spectrum width displays) are identified using the powers from the long-PRT data. Figure 9 shows plan position indicator (PPI) displays of unfiltered (left panels) and filtered (right panels) spectral-moment estimates. As mentioned before, dominant ground-clutter contamination can be readily distinguished by its biasing effects on weather signals as compared with the surrounding regions of uncontaminated weather signals. For this case, dominant clutter contamination can be observed in the unfiltered data as high reflectivity values near the radar (top-left PPI) collocated with near-zero-velocity values (middle-left PPI) and very narrow spectrum width values (bottom-left PPI). After the CLEAN-AP filter is applied, clutter contamination is mitigated, which is evident by the spatially smooth reflectivity, velocity, and spectrum width fields (right panels) that are typical of weather returns. Whereas these images cannot be used to accurately measure filtering biases, the qualitative assessment of spatial textures and magnitudes supports performance expectations for the CLEAN-AP filter. That is, in most cases, it appears that the spectral moments of the underlying weather signal are reasonably recovered. There does seem to be some loss along the zero-velocity isodop close to the radar where the velocity appears to have a small gradient (i.e., negative velocities transitioning to positive velocities). However, the spatial texture and magnitudes of the filtered reflectivity field in regions where the velocity field is near zero are consistent with those in neighboring regions where the velocity field is away from zero. Thus, as expected from the results in Fig. 6, reflectivity biases introduced by the CLEAN-AP filter in this case are small and not visually apparent.

As another example, the CLEAN-AP filter was applied to $I$ and $Q$ samples collected with the dual-polarized KVNX at Vance Air Force Base, Oklahoma, on 8 March 2011 at an elevation angle of 0.5°; 17 samples per dwell at a PRT of 3.107 ms were processed for reflectivity and polarimetric-variable estimates, and 61 samples per dwell at a PRT of 0.847 ms ($v_a = 30.6$ m s$^{-1}$) were processed (independently) for Doppler velocity and spectrum width estimates. Figure 10a shows PPI displays (enlarged to show coverage out to ~65 km from the radar) of unfiltered (left) and filtered (right) reflectivity (top), velocity (middle), and spectrum width (bottom) estimates. Extensive strong ground-clutter contamination can be observed close to the radar in the unfiltered data where moderate-to-high reflectivity values are collocated with near-zero-velocity and very narrow spectrum width values. However, spatial textures and magnitudes of the corresponding filtered fields are smooth and consistent with those of regions with no apparent ground-clutter contamination. Thus, similar to the previous example, the fields of filtered data qualitatively confirm that the CLEAN-AP filter can mitigate ground clutter signals in regions with varying degrees of contamination. Further comparisons show that, as expected, the impact of the filtering process in uncontaminated regions (e.g., the region north of the radar) is not visually apparent. Figure 10b contains PPI displays of differential reflectivity, differential phase, and correlation coefficient for the same region as in Fig. 10a. More evidence of ground-clutter contamination for this case can be seen in the increased variability (textures) and biases of unfiltered polarimetric-variable fields over clutter-contaminated regions [the reader is referred to Park et al. (2009) for a good synopsis of the signatures of ground clutter in the fields of the different polarimetric variables]. After filtering, the same regions exhibit textures that are more consistent with those seen in regions devoid of clutter contamination (e.g., north of the radar). Thus, the qualitative assessment of these examples supports the quantitative simulation results in the previous sections and confirms that the CLEAN-AP filter can effectively mitigate ground-clutter contamination for all meteorological variables in both single- and dual-polarization weather cases.

5. Conclusions

This paper introduced the CLEAN-AP filter as a novel approach for ground clutter mitigation on single- and dual-polarimetric weather radars. The proposed technique operates on samples from a single radar-resolution volume and addresses both aspects of the clutter-mitigation process: selective filter application and effective clutter suppression. The CLEAN-AP filter works by identifying the spectral leakage caused by ground clutter signals in the argument of the lag-1 autocorrelation spectral density. Being coupled with an adaptive data window selection mechanism, the CLEAN-AP filter is capable of mitigating the adverse effects of ground clutter without unnecessarily degrading the quality of the meteorological data.

Simulations and real data were used to evaluate and illustrate the performance of the CLEAN-AP filter under a wide variety of conditions. It was shown that the CLEAN-AP filter comfortably meets the ground-clutter...
suppression requirements of the WSR-88D. That is, in the majority of cases, it provides effective suppression of ground clutter returns for clutter-to-signal ratios of up to (at least) 50 dB with minimal biases in the resulting meteorological variables. However, as with most filters that operate on a single-radar-resolution volume, the CLEAN-AP filter exhibits biases in the meteorological-variable estimates corresponding to weather signals with near-zero Doppler velocities and very narrow spectrum widths (the so-called zero-velocity isodop). Further research is underway to exploit polarimetric information to improve the robustness of the spectral clutter-extent determination (Kilambi et al. 2013). In addition, work is ongoing to extend the functionality of the CLEAN-AP filter to other radar waveforms, such as systematic phase coding and staggered PRT.

Although the CLEAN-AP filter has been shown to meet the ground-clutter-suppression requirements of the WSR-88D, more comparisons with the current operational techniques are needed. Nevertheless, the analysis documented in this work confirms that the CLEAN-AP filter can provide effective mitigation of ground-clutter contamination when implemented on operational weather radars.

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