NOTES AND CORRESPONDENCE

Reducing the Effect of Ground Clutter on Wind Profiler Velocity Measurements

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ABSTRACT

It is well known that the presence of ground clutter may severely bias radar measurements of the Doppler shift, particularly with wind profilers undertaking boundary layer measurements. It is shown both qualitatively and quantitatively with simulated data that a simple detrending of the time series data is often sufficient to significantly reduce the clutter problem. Finite impulse response filters are also investigated. Improvements are seen when long records are filtered prior to spectral analysis of the time series. The results are not very sensitive to the width of the filter (within reason) as long as the filter width encompasses the clutter spectrum.

1. Introduction

The presence of ground clutter in Doppler radar measurements can severely degrade velocity estimates. This is particularly true for radar wind profilers because they routinely detect very weak signals from the clear air, and even weak clutter may severely bias wind estimates. These biases are then magnified due to the geometric conversion of radial velocities to horizontal winds. Furthermore, profilers using UHF frequencies (e.g., 404 and 915 MHz) seek wind measurements at near ranges of a few hundred meters where clutter signals are strong. Fading of the clutter echo because of atmospheric turbulence, wind-blown trees, wires, etc., gives it a finite spectral width that may in turn be spread farther in the spectrum by window effects.

Clutter has long been recognized as a serious problem, but the clutter rejection algorithms used in routine profiler operation are often very simple, such as a replacement of the DC spectral component and several points around it with a mean value (e.g., Barth et al. 1994) and may themselves produce substantial biases. This is largely a historical artifact as early profilers processing data in real time had severe memory and processing speed restrictions requiring simple algorithms. The ground clutter problem in profiler data is in many ways easier than that for weather radars. The reason for this is twofold. First, the data records are much longer so that a better statistical representation of the clutter signal is possible, and second, the clutter spectral width to clear air spectral width ratio tends to be smaller in profiler data compared with weather radar data. The latter is a result of using fixed beam directions so that the clutter signal is not broadened by antenna motion and the relatively wide beamwidths of most profilers producing large beam broadening of the Doppler spectra. However, filtering of low velocity data is more critical in profiler measurements.

The only other published profiler clutter suppression algorithms are a least squares approach to clutter removal in the time domain (Sato and Woodman 1982) and a neural net approach employed by Clothiaux et al. (1994). Processing techniques after the spectral moments are estimated, such as consensus averaging (Strauch et al. 1984), do not help the situation as the biases will be in every velocity estimate. Frequency domain techniques such as half-plane subtraction (Passarelli et al. 1981), which removes the spectral components symmetric about zero frequency, are only applied to profiler data as a last resort, as profilers are often dealing with small Doppler shifts and substantial amounts of the ''signal'' component are also removed. In general, techniques to remove the clutter signal prior to the spectral processing are desirable.

The aim of this paper will be to quantify the magnitude of the biases using common profiler clutter suppression techniques and to explore some options using

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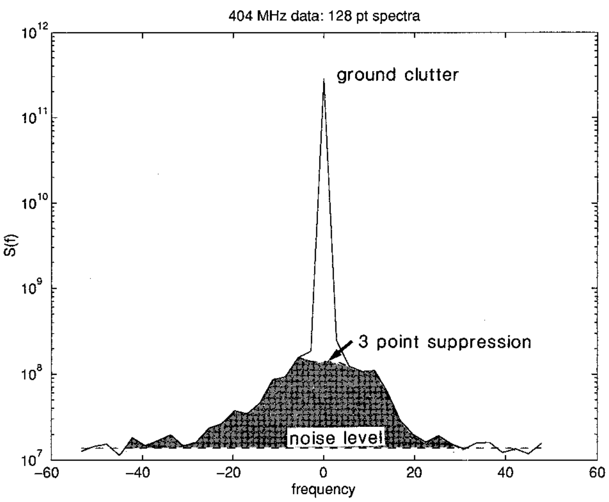

FIG. 1. Figure showing a 3-point linear interpolation about the DC spectral value (dashed line). In this case the insertion of the average value of the spectrum about the window has been used (Barth et al. 1994), although a linear interpolation would be superior. The interpolation is often over even more points for sites with serious clutter problems. The moments are estimated over the shaded area where the power spectral density is above the noise level from the peak out to a frequency where the spectrum first crosses the noise level. Frequencies are given here and in the remaining figures as degrees per time step (as for a pulse-pair estimator) so that $180°/\Delta t$ is the Nyquist velocity.

simple spectral processing. It will be demonstrated with both real and artificially generated data that some extremely simple preprocessing decreases the problem of fading clutter enormously.

2. Usual profiler processing and some examples of wind profiler Doppler spectra

For the sake of discussion, we will begin after the collection of time series of a coherently averaged complex signal. The most common mode of operation is to collect a time series of 64–256 points, calculate its power spectrum using an FFT, and then average several successive spectra together. The spectral moments are estimated from the averaged power spectrum. A Hanning window is frequently used. The moments are estimated using that portion of the power spectrum that lies within a window corresponding to an interval about the spectral peak that is above the first crossing of the noise level (Strauch et al. 1984) (Fig. 1) or a least squares fit of a Gaussian function to the spectrum about its peak (Yamamoto et al. 1988). The accuracy of these techniques for clean data (i.e., no clutter) has been thoroughly explored (e.g., Yamamoto et al. 1988; May et al. 1989; May and Strauch 1989; and others). Another common approach to moment estimation is a pulse-pair processor where the phase of the autocorrelation function at the first lag is used to estimate the Doppler shift (e.g., Woodman and Guillen 1974).

No clutter correction is usually done for pulse–pair-type estimators, although it is possible (Sato and Woodman 1982). For the spectral processing, a frequently used and simple method takes a sequence of points symmetric about the DC spectral point and replaces them by either a linear interpolation between or the mean value of the points immediately outside the sequence (Fig. 1). The latter procedure is employed with the National Oceanic and Atmospheric Administration (NOAA) demonstration network profilers (Barth et al. 1994). The use of interpolation or mean value replacement makes little difference to the results. The mean value replacement of n points is referred to as n-point suppression. This procedure can clearly cause problems since the clutter window often has a significant width compared with the desired clear-air signal.

An example of the real part of a time series segment and the corresponding 4096-point power spectrum collected with a 404-MHz profiler is shown in Figs. 2a,b. The large amplitude, slowly fading part of the time series is the clutter, while the rapidly fading part is the signal plus noise. These are manifested in Fig. 2b as the narrow central peak near zero velocity and the broader peak, respectively. The power spectrum distinctly shows the clutter peak with a spectral width about one-fifth of the clear-air signal.

Most profilers use small segments of the total time series, estimate the Doppler spectrum, and average power spectra from successive segments (Fig. 2c). The clutter peak is narrow if a rectangular window is used but has wide ''skirts'' of lower signal levels because the resulting window function in the spectral domain is $[\sin(x)/x]^2$ (Passarelli et al. 1981). For cases with large amplitude clutter, these skirts are often of similar magnitude to the clear-air signal. The main peak is slightly broader if a Hanning window is applied, but the amplitude of the skirts is much reduced.

If the time variation associated with the fading clutter is reasonably approximated as a trend in the time domain over the interval used to calculate individual power spectra, then a simple removal of a linear trend from the short complex times series segments (detrending) will substantially reduce the impact of the clutter. The trend is estimated using a least squares fit of a straight line to the complex time series segment. The resulting line is then subtracted. The benefit of this is seen in the ''detrend'' curve in Fig. 2c.

The use of a time series that is too short will not provide sufficient velocity resolution or be long enough relative to the signal fading time for reliable velocity estimation (Doviak and Zrnic 1993). If time series of more than about 128 points are used, there are segments with considerable curvature of the clutter trend and a linear trend does not well approximate the clutter signal. A time series of 64–128 points is a suitable compromise. For longer time series, removing clutter by fitting a polynomial is possible, but this is just approximating the use of a digital filter. In this case it is preferable that the time series should be as long as possible, so that a

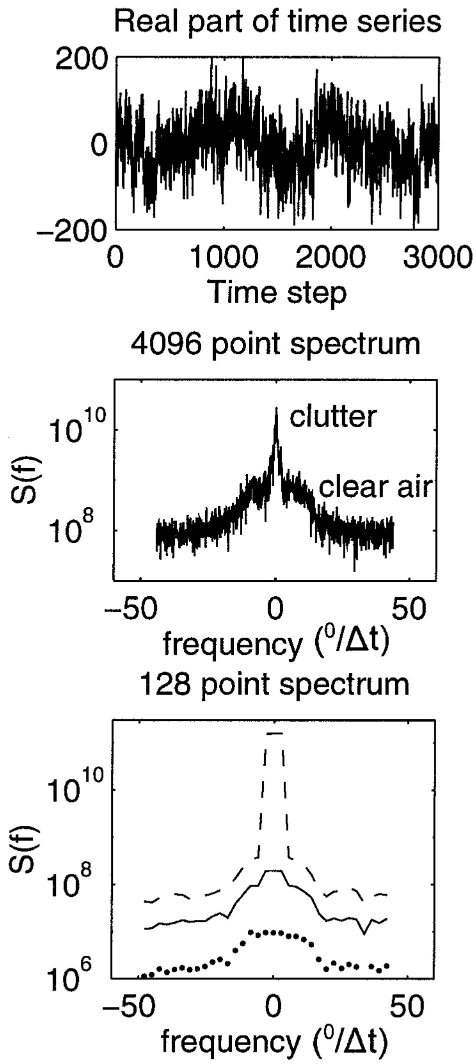

FIG. 2. Three panels showing a segment of the real component of the complex times series measured with a 404-MHz profiler in Colorado, a section of the average of six 4096-point power spectra, and a section of the corresponding 128-point spectra using that same time series. The three curves in the lower panel for the 128-point spectra are for the spectra calculated using the raw data (i.e., a rectangular window, solid) and where a Hanning window has been applied to the 128-point time series segments (dashed) and where a linear trend has been removed from each or the 128-point segments (detrended, dotted). The spectra are offset for clarity. The peak at zero frequency has been interpolated through. All the spectra are plotted on logarithmic scales.

good representation of the clutter is obtained and, for example, an FIR filter (finite impulse response) (see appendix and Press et al. 1989) can be used. The FIR is widely used in weather radar, and its implementation with wind profilers is greatly facilitated because the time records are much longer. This type of approach is now possible with increased, low-cost computer power. However, short (in terms of time series length versus clutter fading time) time series may still need to be collected for RASS (radio acoustic sending system) operation since a large Nyquist velocity is required and memory limitations again become important. Where filters are employed on long time series, the resulting time series can still be broken up into segments. The alternative long spectral approach requires either averaging of successive spectral points or equivalent methods that allow accurate moment estimation when the standard deviation of the spectral coefficients is equal to their mean. Thus, there is little real gain in spectral resolution.

It is apparent that improved processing techniques are available and are easily implemented (not surprising considering the simple techniques presently used). The remainder of the paper will look at these approaches in a more quantitative manner. This is best done by constructing artificial data where the ''true'' values are known and potential biases can be investigated.

3. Simulation procedure

The generation of artificial data with appropriate signal statistics have been widely used to study various radar velocity estimators (e.g., Zrnic 1975; and many others since). A ''clean'' dataset (i.e., no clutter) can be generated by taking a (Gaussian above a noise floor) power spectrum, say over 4096 points, and multiplying each spectral coefficient by $-\ln([0, 1])$, where [0, 1] represents a random number taken from a uniform distribution between 0 and 1. An amplitude spectrum is then simply obtained by taking the square root of the power spectrum. This results in each spectral point having an exponential power distribution and Rayleigh amplitude distribution. The spectral phase is given by 2π times random numbers taken from a different [0, 1] distribution. A complex time series with appropriate statistical characteristics and known Doppler shift and spectral width is obtained by taking an inverse Fourier transform of the resulting complex amplitude spectrum, and segments of the time series are then used as data.

Clutter can be added to the above time series in several ways. The clutter may be approximated by the sum of a few slowly varying sinusoids or alternatively, as is done here, a separate time series is obtained in the same manner as the previous paragraph but with a narrow power spectrum corresponding to slowly fading clutter. This latter approach tacitly assumes that the clutter will have similar statistical characteristics to the weather signal, which is reasonable. An example of the real part of a complex time series is shown in Fig. 3. Note the similarity to the example of an observed time series in Fig. 2, although the clutter amplitude is about a factor of 2 higher compared with the clear-air signal in the observations.

To keep the discussion general, the frequencies will be given as degrees of phase change per time step (Δt) (as for a pulse-pair estimator), with the Nyquist velocity corresponding to $180°/\Delta t$. Each velocity estimate is made from a 4096-point time sequence broken up into 128-point segments. Thirty-two power spectra (after

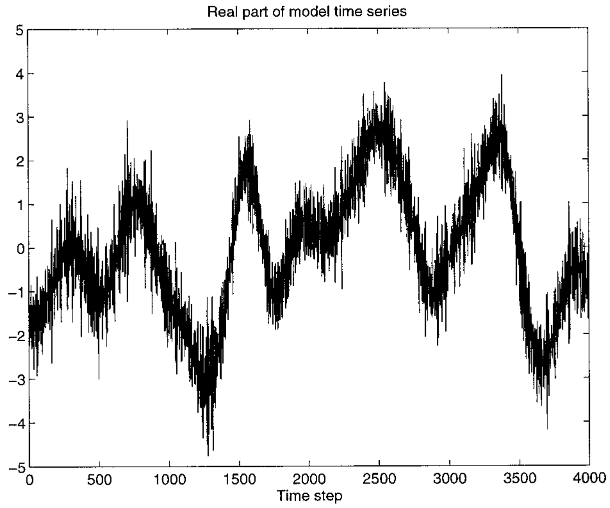

FIG. 3. The real part of some simulated time series. The peak-to-peak clutter amplitude is 20 times that of the signal component.

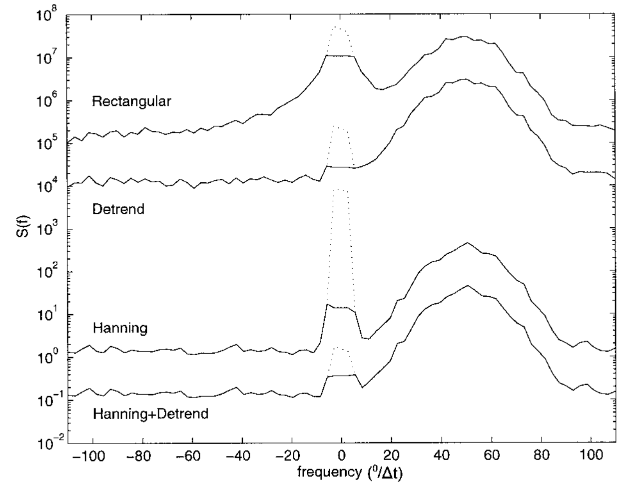

FIG. 4. Sample of the simulated, averaged 128-point spectra for raw data, where a Hanning window has been applied, where the 128-point time series have been detrended, and where both a window and detrending have been performed for 1-point suppression over the DC component (dotted) and 3-point suppression (solid) The spectra are offset for clarity. The clear air spectral width $\sigma_{vn} = 0.03$ for this and subsequent figures. The results are not sensitive to the value of σ_{vn}.

windowing/detrending/filtering of each 128-point segment) are then averaged. A number of values around zero frequency are replaced by the average of the values on either side of the suppression window, as in the NOAA network profilers (Barth et al. 1994). The velocity is then estimated using the technique described in Strauch et al. (1984) and May and Strauch (1989). The point of maximum power spectral density is found, and the first moment of the spectrum is calculated over an interval from the peak down to where the spectrum first crosses the noise floor on either side of the peak (shaded area in Fig. 1). This algorithm is widely used, for example, by the wind profiler demonstration network profilers, Radian boundary layer profilers, and the Aeronomy and Environmental Technology Laboratories of NOAA research profilers. Of course, other algorithms are possible and will suffer to a greater or lesser extent from clutter problems. Biases and standard deviations are estimated from a collection of 40 simulated datasets. Here, the bias is defined by the mean velocity estimated from the data subtracted from the model Doppler velocity.

The model signal-to-noise ratio is set at 13 dB, a fairly high value, but clutter is most important at lower altitudes where the signals are strong. The normalized spectral width σ_{vn} is defined as $\sigma_{vn} = \sigma/2V_n$, where σ is the spectral width and V_n is the Nyquist velocity. The results to be discussed use a single value of σ_{vn} (0.03), but simulations have been performed over a range of widths (0.015–0.12). The results are not very sensitive to the spectral width of the clear-air signal. Obviously, there are some quantitative differences, but these are small and the discussion is quite general.

4. Impact of clutter

a. Standard processing

As mentioned, standard processing uses either the raw time series of complex signal amplitude (rectangular window) or a series with a Hanning window applied to them. Figure 4 shows a sample of the averaged power spectrum where these two approaches have been used. Note the similarity to the observed spectra shown in Fig. 2c. In Fig. 4, the replacement of only the DC component (dotted) and the effect of 3-point suppression (solid) is illustrated. As discussed previously, energy has been fed from the clutter into the adjacent frequencies by the Hanning filter, but the power at frequencies greater than 1 point away from DC is reduced compared to the rectangular window (raw) case. The $[\sin(x)/x]^2$ frequency response of the rectangular window is easily seen. With the 3-point suppression a clutter peak is still evident in the Hanning spectrum, but its amplitude relative to the raw spectrum is much reduced.

Figure 5 shows the biases of the Doppler velocity estimate as a function of the Doppler frequency for different amounts of clutter suppression and using the different processing techniques. Clearly, there is a significant problem with the rectangular window when the clutter is as severe as in these simulations. The algorithm is almost always estimating the ''clutter velocity'' rather than the clear air. Large biases still occur when several spectral points are suppressed. On some occasions the errors are associated with the algorithm selecting the clutter peak rather than the clear-air peak, but biases also occur because of the extensive skirts of the $[\sin(x)/x]^2$ shaped clutter peak when the clear-air peak is selected.

While this discussion is primarily concerned with spectral processing, it is worth noting that the pulse-pair algorithm is essentially equivalent (at least for high signal-to-noise ratio data) to 1-point suppression (since the power spectrum and autocorrelation are a Fourier

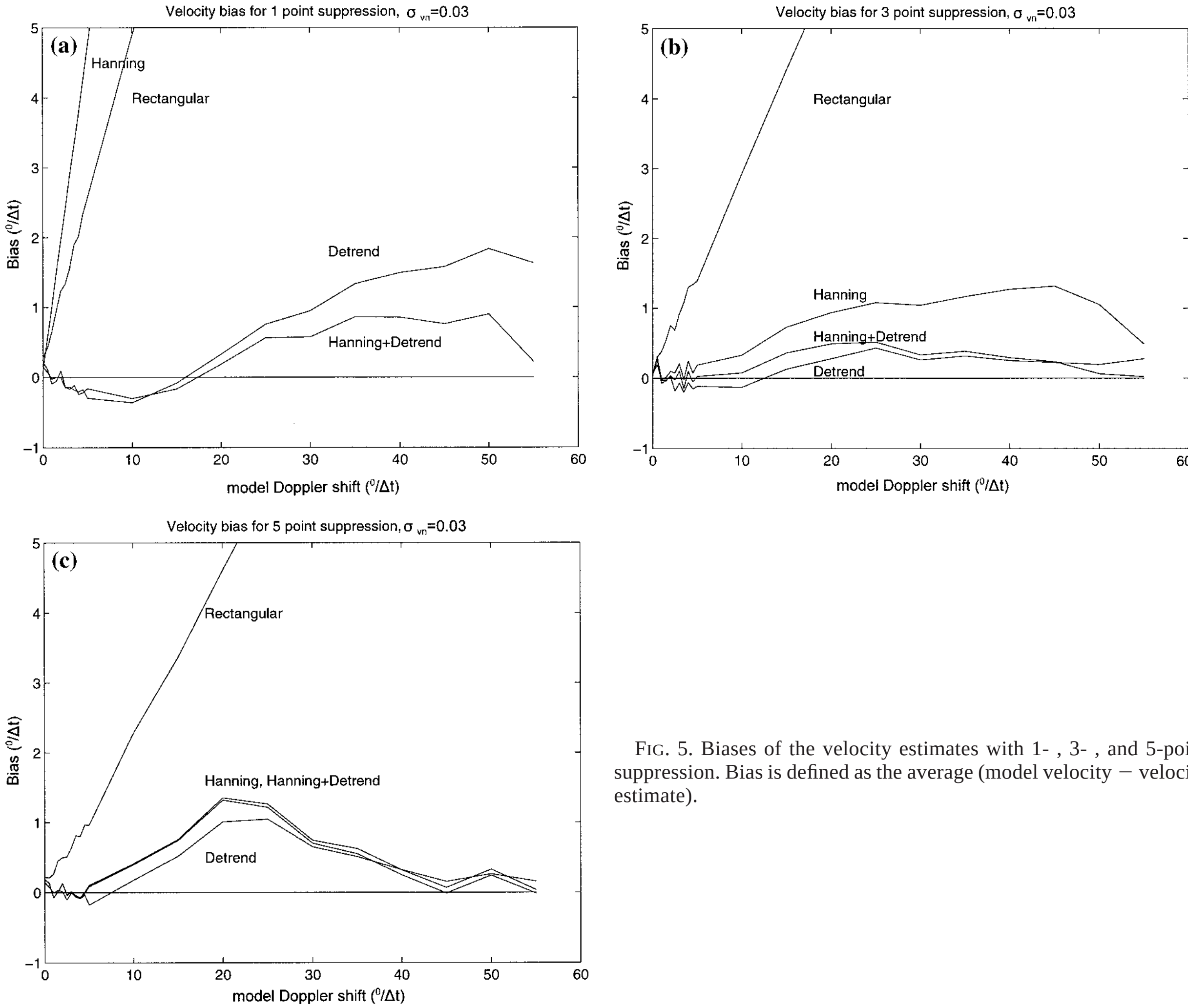

Fig. 5. Biases of the velocity estimates with 1- , 3- , and 5-point suppression. Bias is defined as the average (model velocity − velocity estimate).

pair), unless larger values of lag are used as in Sato and Woodman (1982). Thus, clutter has a large impact on pulse–pair-processed data.

b. Trend removal

The benefits of detrending the time series are demonstrated in both observed and model data (Figs. 2 and 4). Detrended data clearly has less residual clutter signal and the biases inherent are much reduced. This also allows the use of smaller numbers of suppressed spectral points.

This inference is confirmed by the results of the simulations. Even 1-point suppression is sufficient to limit the biases to small values of less than $2°/\Delta t$ (Fig. 5) and less than $1°/\Delta t$ for 3-point suppression (for a typical Nyquist velocity of 15 m s^{-1}, $1°/\Delta t$ corresponds to 0.083 m s^{-1}). There is little difference in these cases whether a Hanning window is used or not, although it is reasonable to expect that if the clutter is even worse, 3-point suppression and a Hanning window would be advisable. There are some residual biases because of the clutter peak, even at large Doppler shifts. This has been eliminated with a 5-point suppression, but at the cost of larger biases at small velocities.

The suppression of spectral points near DC is not without cost, particularly for narrow spectra. While clutter, of course, causes biases, so too does the suppression of points over an interval. This is particularly evident in the bias curves for suppression over a wide interval. A significant part of the clear-air component is removed, and biases occur. Because of this, the largest effects occur if the true peak is near the edge of the suppressed frequency region. The suppression procedure causing biases is most evident when the spectra are narrow, and there is the possibility that most of the desired signal is being suppressed. Simulations with suppression over a large interval, say 9 points, have been performed, and biases greater than $7°/\Delta t$ were seen for such cases. This occurs whether or not there is clutter actually present in the spectra. The standard deviation of the estimates also increases where a significant part of the clear air

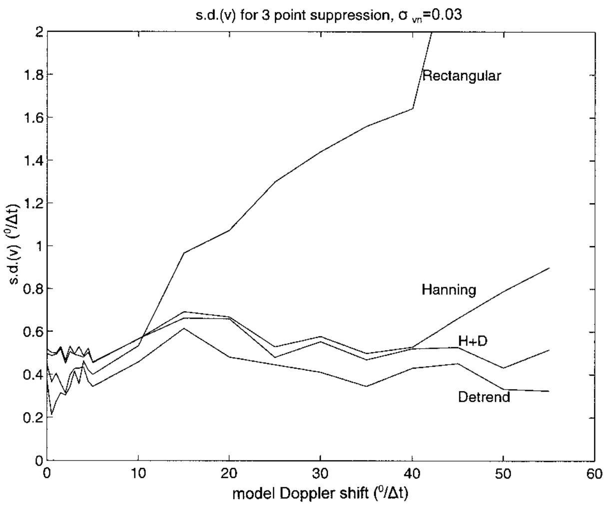

FIG. 6. Standard deviations of the velocity estimates with 3-point suppression.

spectrum has been suppressed. Alternatives to suppression of spectral points near DC, such as fitting the signal and clutter spectral peaks (Sato and Woodman 1982), can be used, and these methods would also benefit by removing as much of the clutter signal as possible by detrending.

If the clutter is fading faster than considered here, simply detrending the data will not be as effective. If the clutter spectral width is doubled, the detrending still gives a very large improvement, but biases of several degrees are obtained for moderate Doppler shifts (not shown). The detrending results are less sensitive to clutter amplitude with a doubling of the clutter amplitude still giving biases of less than a degree with 3-point suppression. Doppler weather radars that have faster fading clutter relative to the sample length because of antenna rotation have used various filters such an IIR (infinite impulse response) or FIR filters to minimize the effect of clutter (see the appendix). Therefore, these will be considered next.

The standard deviations of the estimates are fairly insensitive to the techniques as long as the clutter is reasonably filtered (Fig. 6). Slightly higher values are seen when a Hanning window is used as the effective number of independent points in the time series are reduced.

Since detrending removes a significant part of the clutter signal, it also offers a solution for when pulse-pair estimators are used. Simply detrending the data segments will remove most of the bias as long as clutter does not fade too fast.

c. FIR filters

There are a few issues to be faced before using filters on the data. The primary one is what the spectral width (and form) of the filter should be. The second is the choice of filter itself. FIR filters are selected here for their phase preserving properties, although IIR filters also have their advantages. An IIR filter with similar suppression of the filtered signal as an equivalent FIR filter can be constructed with many less terms, and is therefore simpler to implement, but has inferior phase characteristics. Doppler weather radars have used IIR filters (e.g., Banjanin and Zrnic 1991) because of their shorter length, but this is not such an issue with profilers because far fewer range gates are sampled, the sampling rate is much slower, and relatively long time series are collected. A Hanning window is also used in the filtering process.

FIR filters with many terms are required for a filter response that is sufficiently deep and narrow. Too few terms produce filters that are either too broad (and filter too much of the desired signal) or too shallow (so that clutter remains). The prime reason a filter may be chosen over detrending, especially given the results of the previous section, is that it may be applied over records long enough that the clutter is reasonably well sampled. A 1024-point filter has been constructed (see the appendix).

When simulations are conducted over a range of Doppler shifts, the standard deviations of the velocity estimates with detrended time series and the FIR filter shows similar results, and the biases are smaller with the FIR filtered data and 1-point suppression compared with detrended data (Fig. 7). When 3-point suppression is used, the bias for the filtered data is reduced below $0.2°/\Delta t$ at all Doppler shifts. Two filter widths varying by a factor of 2 have been used and the results are similar, although biases remain if the filter is so narrow that some of the clutter is passed. The standard deviations of the estimates using the filtered data is about $0.6°/\Delta t$ and is fairly independent of velocity. The 1024-point filter was truncated to 128 points, and the results were similar to that obtained with detrending.

5. Discussion and conclusions

This note has examined some techniques for removing the effects of ground clutter and what biases in the measurements result. Biases of a few degrees are significant. For example, in the study of weak vertical motions or for low wind speed conditions, these biases are comparable with the meteorological signal. Thus, the minimizing of the effect of clutter is important.

Substantial improvements in the treatment of ground clutter signals with wind profilers can be achieved with little extra overhead. Simply by detrending data, substantial improvement is possible. With the detrending approach, it is advisable that 3-point suppression be used. This suppression is sufficiently narrow compared with the typical clear-air widths to cause little attenuation of the desired signal but reduces the clutter to small levels.

In the longer term, the use of digital filters may be

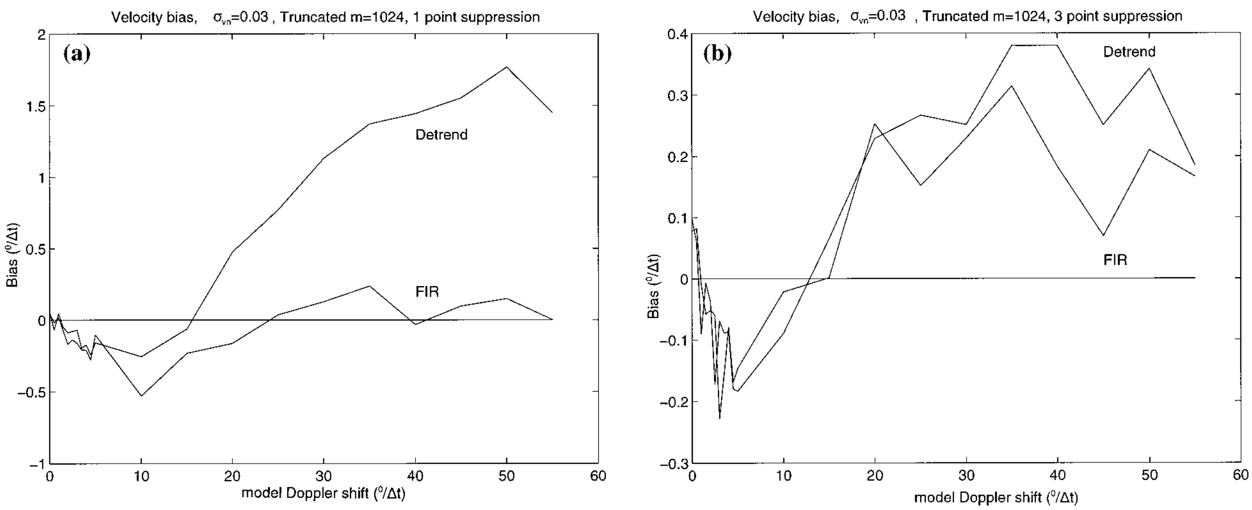

FIG. 7. As for Fig. 5 but with an $m = 1024$-point FIR filter and (a) 1-point and (b) 3-point suppression.

desirable but may require an order of magnitude or more greater processing. These have only been briefly looked at here but may be a key component in a more complex adaptive approach to clutter rejection. That is, in conditions where the clutter is relatively broad, a wider filter could be utilized. An approach to test for clutter could be along the lines of a noise estimation algorithm by Hildebrand and Sekhon (1974). They sort the power spectral points into ascending amplitude and detect a break in the slope of the resulting distribution where the signal rises above the noise level. Similarly, there is another break in the distribution if clutter is present at large amplitudes. This could allow the detection of remaining clutter so that the data could be refiltered with a wider filter. This approach may also be able to differentiate precipitation echoes in 50-MHz profiler data, and it has been used to detect/remove bird contamination with 400- and 920-MHz profiler data (Merritt 1995). The length of the required FIR filters is also of concern, and IIR filters should be investigated as well.

Filters may also be adapted to reducing sea clutter, but alternative techniques are required for clutter from targets such as birds and aircraft. For weather radars, the results of this paper suggest it may be useful to filter time series for several successive azimuth samples together as a single time series and then use segments of the filtered time series to retain the azimuthal resolution.

APPENDIX

FIR and IIR Filters

The following synopsis is derived from the discussion of FIR and IIR filters in Press et al. (1989), and more detailed discussions are available in that book and references contained within. A linear filter of a sequence x_k input produces an output sequence y_k by the following formula:

$$y_n = \sum_{k=0}^{M} c_k x_{n-k} + \sum_{j=1}^{N} d_j y_{n-j},$$

where the $M + 1$ coefficients c_k and N coefficients d_j define the filter response. If $N = 0$ (i.e., there is no second term), the filter is nonrecursive and inherently stable. These filters are known as FIR filters. If $N \neq 0$, the filter is recursive and, if poorly designed, may be unstable. These filters are known as IIR filters and include Chebyshev and Butterworth filters. In practice, there are well-defined conditions for stability. As discussed, an IIR filter that has similar bandpass characteristics will, in general, have fewer terms than an equivalent FIR filter, but an FIR filter is intrinsically phase preserving.

The FIR filters used in this paper were obtained using

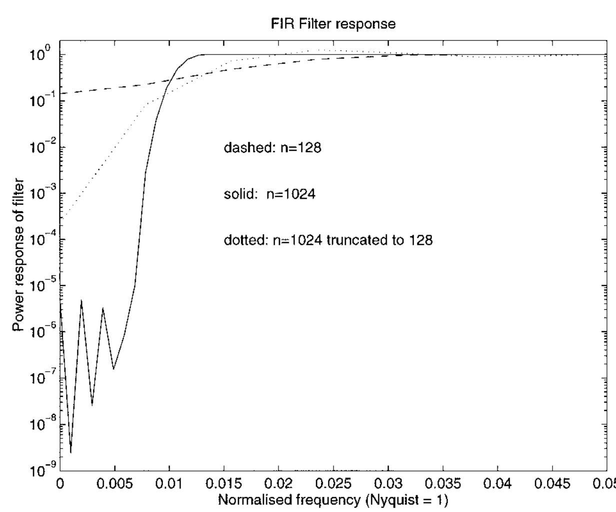

FIG. A1. Frequency response of three FIR filters of width 0.01, where the filter length is 128 (dashed) and 1024 (solid) and a 1024-point filter truncated to 128 points (dotted).

the MATLAB signal processing toolbox. The FIR filter is defined by the number of terms in the filter ($M + 1$) and the width of the filter given in this paper is a fraction of the Nyquist interval. The addition of extra terms allows a better defined filter with a much deeper frequency notch. For example, Fig. A1 shows the frequency response of three FIR filters of different lengths with a width of 0.01. The large number of terms needed for acceptable filtering is a reflection of the narrow frequency range to be filtered. Filters with such a large number of terms have a correspondingly long delay. This is not too bad for profilers where long records are routinely collected. The filter function may also be truncated, reducing the delay, but at the cost of degrading their response. However, the response of the truncated filter may be better in some respects than a ''straight'' FIR filter of the same length. The power responses of 1024, 128, and 1024 truncated to 128-point filters are shown in Fig. A1.

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