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The production of high quality Doppler velocity fields for dual PRT weather radar

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1. Introduction

Doppler weather radar suffer from well known limitations associated with the trade off between range and velocity aliasing. This is particularly severe as the radar wavelength decreases. There are a number of operational 5 cm wavelength Doppler radars around the world and for reasonable maximum ranges of about 150 km, the unambiguous velocity is only about 13 ms^{-1}. Automated processing techniques to de-alias the resulting radar data are fairly limited in there usability for such a small Nyquist. An alternative strategy that has been employed is the use of multiple pulse repetition times. A widely used approach to mitigate this problem is using a dual PRT (Pulse Repetition Time). This may be on a pulse pair to pulse pair basis, where the time between pulses is varied on every pulse pair (referred to as a staggered sampling), or where alternate records of, for example 32 pulses, are sampled at a single, but different PRT (dual PRT). The former has intrinsic advantages for unambiguous unfolding, but the staggered sampling limits the performance of simple ground clutter filters (e.g. Banjanin and Zrnic, 1991). A common approach to avoid this is the latter strategy which is an approximation of the first. This approximation is employed on operational Doppler radars in Canada and Australia, the research radar at ETH and is available on some commercial signal processors (SIGMET, 1992; Joe et al, 1998). However, there are problems unfolding the data if the azimuthal gradient of the radial velocity is large or if the variance in the velocity estimate becomes comparable to the Nyquist velocity. The goal of this paper is to evaluate and demonstrate the advantages and limitations associated with the dual PRT method in the presence of wind fields with large horizontal shears and to assess the magnitude of problems inherent in the dual PRT approach.

Errors in the derived velocity field arise when the assumption of uniform radial velocity breaks down. In, this instance the target pixel is assigned an incorrect velocity interval when its neighbor differs from the target by too much. This may occur even if the individual rays are not aliased. This has implications for the sensitivity of the measurements to both random errors and large gradients. However, the errors in the derived velocity estimate are discrete (multiples of twice the Nyquist velocity of the target pixel) and it is possible to use this information to correct many of the de-aliasing errors. We will also discuss some practical issues related to dual PRT radar operation related to clutter filtering .

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2. Discussion on algorithms for correcting noisy data

(A) Median filtering of the image

A cursory examination of raw velocity images from a dual PRT Doppler radar show two distinct types of errors. The first , and easiest to address is the introduction of speckle. Coherent patches of suspect data are much more difficult to deal with.

An simple approach to removing speckle from an image is to simply smooth the image using a median filter. This will tend to remove isolated bad pixels, but at the cost of lowered resolution, that is, smoothing of the radial velocity field. A median filter tends to retain strong average gradients in the fields. There other possible approaches, such as consensus averaging the velocities over a small region in a manner similar to that used with wind profilers, but for this application there is little obvious advantage. The median filter will give a reference for the possible improvement of more complex methods that utilize the knowledge of the quantized nature of dual PRT aliasing error characteristics.

The approach taken here is to replace the target pixel's velocity with the median value obtained by taking a 3*3 matrix of pixels centered on the target. A 3*3 was chosen rather than, for example, a 5*5 array after examination of data with some significant real velocity gradients and subjectively rejected as smoothing the data too much. This will depend on the range and resolution of the data and more sophisticated examples such as taking all the pixels within a box of some physical size may be more appropriate.

Another decision to be made in the filtering process is how to handle missing data, i.e. not all the 3*3 array may have valid velocity estimates. The rules chosen here are that (a) the target pixel must be valid and (b) the median is then calculated on as many points within the 3*3 array that are valid. There was some experimentation on whether a threshold should be set as a minimum number of required point, however it was found that setting any kind of threshold quite severely decreased the availability of clear air velocity data, particularly at longer ranges. Therefore, the Sydney radar uses a threshold of 1 at the cost of passing some speckle through the system.

(B) Laplacian correction

The above is straightforward, but does not make use of our knowledge of the unfolding errors. It is easy to see that the errors in unfolding will be discrete, as ±2*Vn of that beam or ±4*Vn etc. We can make use of this information for better unfolding with no loss of resolution. This algorithm looks at the points surrounding the target point. The n surrounding points are summed and n*target point is subtracted. If the target has a serious de-aliasing error, this will result in a large value being obtained. Then this difference is calculated with the target point being offset by multiples of twice the Nyquist velocity to see if a small value can be obtained. If so, then this is substituted. This algorithm can be performed over several iterations. Then if quality is still a concern , a median may then be performed.

	PRF's	Angular resolution	Antenna rotation rate	# samples
Canada	1200/ 900	0.5	1.5 RPM	64
Aust.	1000/ 750	1.0	3 RPM	40

Table 1: Operational radar characteristics.

3. Algorithm performance

(A) The effect of random measurement errors

Simulated data with errors calculated using the theoretical relations in Doviak and Zrnic (1993) have been produced. The de-aliasing error rates are very low (<5% for typical Cband configurations) until the rms errors approach the Nyquist velocity (Joe et al, 1998). Even, so, both the median filter and Lapacian filter successfully clean up the data, with the Laplacian being slightly more effective. The Canadian and Australian radars use slightly different configurations, but the expected error rates are similar. The error rates have been compared with the apparent rate for data in a uniform stratiform rain situation. In this instance the Laplacian corrected data is used as "truth". The error rates are significantly higher than for the simulations (~ factor of 2) indicating that meteorological noise is the prime source of de-aliasing error. The filtered fields in this instance look very smooth.

(B) Linear wind shifts

The main source of error for data with a high signal to noise ratio is associated with significant azimuthal gradients of the radial wind component. As discussed by May (2001), if the gradient is large errors may occur even if the data from the individual pixels is not aliased. It can be shown that radial gradients do not case de-aliasing errors.

(C) Mesocyclones and microbursts

A primary source of error on dual PRT radar observations is associated with the azimuthal gradients of the radial wind component. These have been characterized using simulations and observations in the previous section. However, the type of weather systems where these problems are expected to be most severe are in tornado and microbursts, although these are really special cases of the previous case with limited spatial extent. This has been explored using simulated data by May (2001). In this section we will analyze a mesocyclone that was observed in a severe thunderstorm during the Sydney 2000 Forecast Demonstration Project (Keenan et al, 2001; Sills et al, 2001).

Data from 2 tilts corresponding to heights of about 300 m and 3 km are shown in Fig. 1. A clear hook echo is seen in the reflectivity data at both elevations. The uncorrected radial velocity shows some similarity to the striped structures shown by May 2001, although the lack of erroneous data at the sharp cyclonic boundary at the upper tilt is unexpected. Note that the speckle in the image will produce unacceptable false alarm rates in automated mesocyclone and tornado vortex detection algorithms if this is not taken into account by the algorithm (Burgess et al, 2001). This is build into the CARDS algorithm and discussed thereby Sills et al(2001). The data has been subjected to both filtering and Laplacian correction procedures with somewhat similar results. Of course the median filtering results in a slightly smoother field but the same data points have all been corrected except a small number of pixels in the low reflectivity regions. There are clear mesocyclone signatures in both tilts, and the upper tilt also contains an anticyclonic vortex signature adjacent to the mesocyclone. In any case, the corrected data is clearly of high enough quality for automated detection algorithms to find the vortex and have minimal false alarms associated with data quality. This is despite a large number of pixels being corrected, 25% in the upper tilt and ~ 13% in the lower.

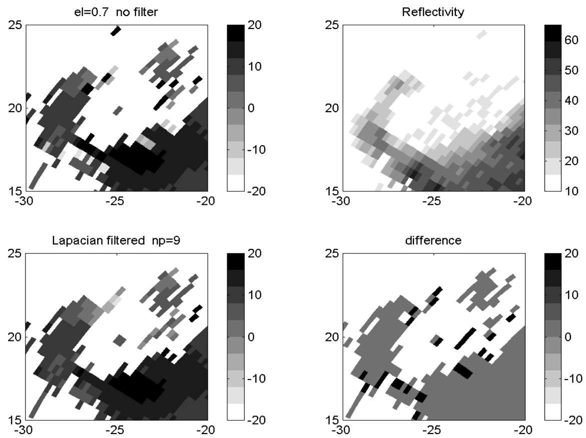
4. Clutter problems and some practical issues

There are a number of practical issues to be addressed. For example, the operational implementation of the radar in Australia has a fixed set of coefficients for the digital clutter filters. This has the effect of producing filter characteristics that are slightly different for the 2 PRF's and some spoking of the reflectivity values is seen. In extreme cases this may be about a dB. In Canada, the clutter filters are implemented in a block processing scheme using a FFT approach circumvents this problem at the expense of greater signal processing requirements.

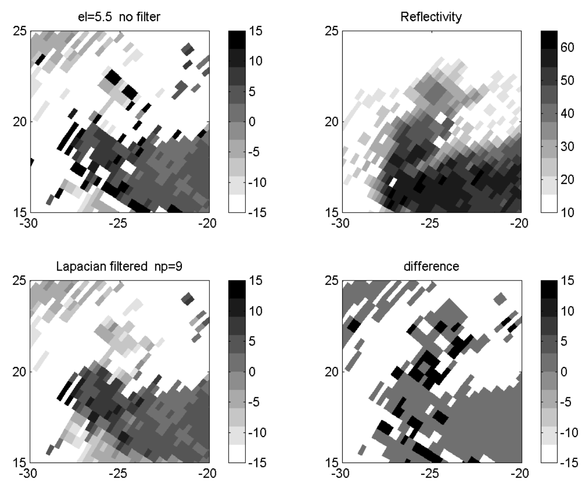
A well known problem with the dual PRT approach is that the filter notch will appear at $\pm 2V_N$ for the particular rays. This can be a problem in larger wind speed regimes. Particularly bad data is obtained if this corresponds to ranges and elevations with large amplitude ground clutter. This is evident in Fig 2 where the data is very noisy. This occured with wind speeds of about 26 ms^{-1} (twice the higher Nyquist) in the lowest tilt over the Blue mountains west of Sydney. The Laplacian filter was ineffective in this case and while median filtering helped a little, the data quality was still poor.

5. Conclusions

It is clear that with real radar implementation of dual PRT radar systems some error correction algorithms need to be



(a)



(b)

Figure 1. 4 panel plots showing the original velocity field measured with the Sydney dual PRT radar, the reflectivity field, the corrected velocity field and the difference between the original and corrected velocity fields. The data is taken from 505 UTC, November 3, 2000 during a tornadic event. The reflectivity shows a clear hook echo structure associated with a deep mesocyclone. The two tilts correspond to heights of about 700 m (a, 0.7^{o} elevation) and 3 km (b, 5.5^{o} elevation).

applied to the data in order to obtain high quality data useful for insertion into automated severe weather detection algorithms. In practice this can be achieved and the results look extremely promising. These algorithms are being used in real time in Canada and Australia. The main problem occurs when there is a combination of wind speeds close to the twice the Nyquist velocities of the individual rays and the presence of significant ground clutter contamination,

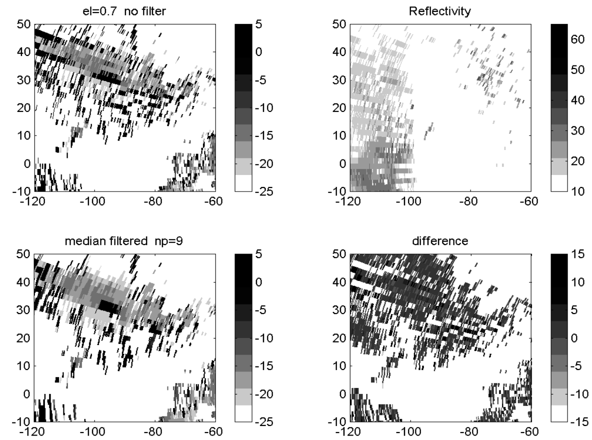


Fig. 2 As for Fig 1, but for clutter contaminated case and median filtering of the data.

although this will also affect conventional radar operation. In spite of the problems, operational forecasters would not go back to single PRF data with the small Nyquist interval.

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