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High quality velocity data using Dual-PRF

I. Holleman and H. Beekhuis

Royal Netherlands Meteorological Institute (KNMI), P.O. Box 201, NL-3730 AE De Bilt, The Netherlands

Abstract. Dual Pulse Repetition Frequency (dual-PRF) technique is available on many operational Doppler weather radars in Europe. This technique is used for extension of the unambiguous velocity interval, but it produces isolated dealiasing errors. A method for the extraction of the velocity standard deviation and the fraction of dealiasing errors from raw velocity data is described. The standard deviation and the fraction of dealiasing errors are related using a simple model. A post-processing algorithm for the production of high quality dual-PRF velocity data has been developed and validated. The post-processing algorithm is very efficient, and it enables further application of dual-PRF velocity data in warning products, dual-Doppler wind field synthesis, and Numerical Weather Prediction models.

1 Introduction

Doppler weather radars are capable of providing wind data at a high spatial (roughly 1 km) and temporal resolution (a few minutes). Velocity information from a Doppler radar can be used for removal of ground clutter, extraction of wind profiles, detection of shear zones, and construction of dual-Doppler wind fields (Meischner et al., 1997; Chong et al., 2000). Furthermore, the wind profiles and radial velocity data can be assimilated into NWP models (Lindskog et al., 2000). Operational application of Doppler velocity data from weather radars is hampered, however, by the infamous limitation of the range-velocity ambiguity. This is particularly true for a C-band weather radar, since its ambiguity limitation is a factor of two more stringent than that of an S-band radar.

Dual Pulse Repetition Frequency (dual-PRF) is a technique for extension of the unambiguous velocity interval of C-band and X-band radars. Dazhang et al. (1984) have proposed this technique wherein velocity estimates are made employing M_1 pulses at one PRF followed by M_2 pulses at the other PRF. Wakimoto et al. (1996) have developed the Electra Doppler Radar (ELDORA), which is an airborne X-band radar with dual-PRF capability. Detailed cross sections through severe thunderstorms and tornadoes have been recorded with this radar and unfolded velocities of more than 80 m/s have been observed. The effect of azimuthal shear of the radial wind on the quality of dual-PRF data has been investigated by May (2001) using a mesocyclone model. May and Joe (2001) have presented an algorithm for correcting dealiasing errors in dual-PRF velocity data. The dual-PRF technique is available on many operational Doppler weather radars in Europe. The application of this technique has been troubled by isolated dealiasing errors which are typical for dual-PRF velocity data.

Here we present an analysis of observed dual-PRF velocity data and an algorithm for production of "high quality" velocity data. The fraction of isolated dealiasing errors determines the quality of dual-PRF velocity data to a large extent. Velocity data containing less than 0.1% outliers are defined to be of "high quality" in this study. A detailed description of the analysis method and post-processing algorithm is given in Holleman and Beekhuis (2002). Characteristics of dual-PRF data are illustrated via different analyzes of observed velocity data. The analyzes confirm that the observed velocity outliers are in fact isolated dealiasing errors. The proposed algorithm for production of high quality velocity data is intended for operational use, and preliminary results indicate that the quality of the velocity data is enhanced significantly and that further use of the data has become feasible.

2 Dual-PRF technique

Dazhang et al. (1984) have proposed to extend the maximum unambiguous Doppler velocity by use of two alternating pulse repetition frequencies, PRF_h and PRF_l. The folding of a measured velocity will be different for the two pulse repetition frequencies. By combining the velocity measurements at the two different PRFs, the unambiguous velocity interval can be extended. It is common practice to choose

Correspondence to: I. Holleman (holleman@knmi.nl)

the high and low PRF in the following way:

$$\frac{\mathrm{PRF}_h}{\mathrm{PRF}_l} = \frac{N+1}{N} = \frac{V_h^u}{V_l^u} \tag{1}$$

where the integer N is the dual-PRF unfolding factor with respect to high PRF unambiguous velocity, V_h^u. With typical applications of the dual-PRF technique, an unfolding factor N of 2, 3, or 4 is used.

A Doppler radar generally determines the radial velocity of the scatterers by autocorrelation of the received signal for subsequent transmitted pulses. During pulse-pair processing the velocity is effectively deduced from the phase jump of the received signal between two subsequent pulses. The difference between the phase jump observed using the low PRF and that observed using the high PRF is employed by the dual-PRF technique to deduce the radial velocity. The primary dual-PRF velocity estimate can be expressed in terms of the original velocities:

$$\tilde{V}_{lh} = (N+1)\tilde{V}_l - N\tilde{V}_h \tag{2}$$

where $\tilde{V}_h$ and $\tilde{V}_l$ are the observed velocities using the high and low PRF, respectively. The standard deviation of a velocity estimation depends mainly on meteorological phenomena, e.g., shear and turbulence. Using Eq. (2) and assuming that the errors in the high and low PRF velocities are uncorrelated, the standard deviation of the primary dual-PRF velocity estimate becomes:

$$\sigma_{lh} = \bar{\sigma}\,\sqrt{(N+1)^2 + N^2} \tag{3}$$

where $\bar{\sigma}$ is standard deviation of the high and low PRF velocities. The standard deviation of the primary dual-PRF velocity estimate increases rapidly with increasing unfolding factor. For an unfolding factor of $N = 3$, the standard deviation is amplified by a factor of 5.

Because of its large standard deviation, the primary dual-PRF velocity estimate is merely used to indicate to which Nyquist interval the original velocity belongs. Occasionally, the deviation of the primary dual-PRF velocity estimate will be so large that the original velocity will be assigned to an incorrect Nyquist interval. This will give rise to clear outliers in velocity data measured with the dual-PRF technique.

3 Radar data

In this study data from the C-band Doppler radar (Gematronik Meteor AC360) in De Bilt have been used. The radar beam width is about 1 degree and the peak power of the magnetron is 250 kW. The radial velocity and spectral width are extracted from the received signal using pulse-pair processing (Sigmet RVP6 processor). The data are averaged to 0.5 km and 1 degree bins in range and azimuth, respectively. During an azimuthal scan in dual-PRF mode, the PRF is alternated between low and high every degree, and the primary velocity estimate is calculated from the actual data and that from the previous degree. The actual velocity data are unfolded using this primary velocity estimate. Dual-PRF scans are recorded every 15 minutes at an elevation of 0.5 degrees and an azimuthal speed of 4 rpm. Employing a high and low PRF of 1000 and 750 Hz, respectively, the extended unambiguous velocity of the system is $V_{lh}^u = 39.9$ m/s.

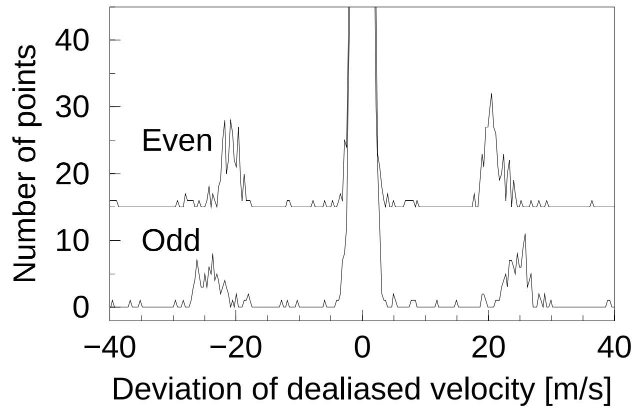

Fig. 1. Histogram of the deviations of each dealiased velocity from the local median velocity for a typical azimuthal scan. Separate histograms are shown for even (with 15 counts offset) and odd azimuths. The central peaks go up to a number of about 12 500 (off-scale). The histograms have been constructed using a velocity bin size of 0.3 m/s matching that of the dual-PRF velocity data.

For both the analysis of dual-PRF velocity data and the validation of the correction algorithm, a set of about 300 different azimuthal Doppler scans is used. The scans have been recorded between 26 October 2001 and 30 November 2001. Only scans recorded at least an hour apart and containing more than 10 000 valid datapoints (10% of total) have been selected.

In this period about twelve depressions moved from the North Atlantic into Scandinavia while the associated frontal systems crossed the Netherlands. Mostly the frontal rain was followed by showers in polar or arctic air. Especially the cold fronts and the showers produced significant weather with rain, snow, thunder, hail, and severe wind gusts. On twenty days within this period the radiosonde wind speed at 850 hPa was higher than the unambiguous velocity of the high PRF measurement, $V_h^u = 13.3$ m/s.

4 Analysis of Dual-PRF data

Dual-PRF velocity data are typically contaminated by (sidelobe) clutter, noise, and outliers. Noise from incidental scatterers is predominantly visible at short range (< 35 km) because the echoes from nearby targets are very strong. Velocity outliers in large areas of high-quality data are typical for data obtained using the dual-PRF technique (Sirmans et al., 1976; Dazhang et al., 1984). A quantitative analysis has been performed to obtain detailed information on the quality and outliers of dual-PRF velocity data. For this, each velocity datapoint in an azimuthal scan, i.e., velocity data as a function of range and azimuth, is compared with the local median velocity. The local median velocity is calculated from the

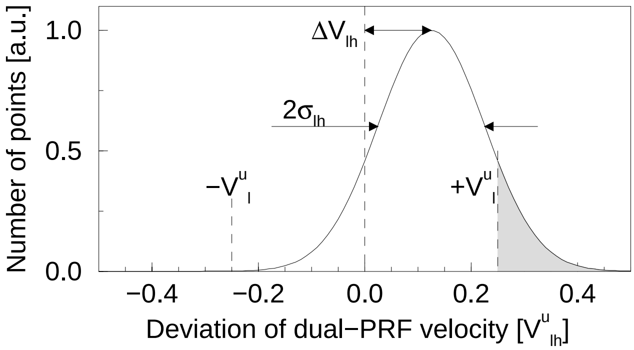

Fig. 2. Scheme illustrating the origin of the dealiasing errors in velocity data obtained using the dual-PRF technique. The distribution of deviations of the primary velocity estimates is depicted. The parameters influencing this distribution, i.e., standard deviation and bias, are indicated. The unambiguous velocity interval of the low-PRF measurement for $N = 3$ unfolding has been indicated in the figure as well. The fraction of incorrectly dealiased datapoints is marked by the shaded area.

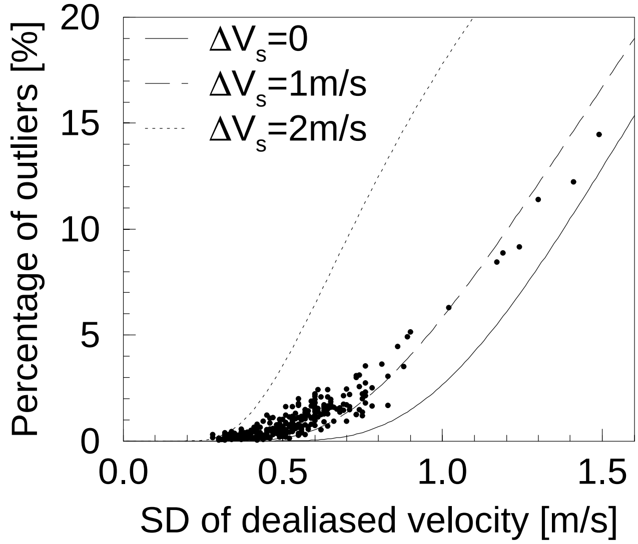

Fig. 3. Fraction of dealiasing errors as a function of the standard deviation of the original velocities. About 300 different azimuthal scans (see Sect. 3) have been used to compile this figure. In addition, three theoretical curves for radial velocity differences of 0, 1, and 2 m/s are shown.

datapoint itself and the surrounding datapoints.

An area measuring five range times three azimuth points (2.5 km $\times$ 3 degrees) is taken, and it is required that at least nine out of the fifteen datapoints contain valid data. The deviation of the datapoints from the local median values has been analyzed. In Fig. 1 histograms of the velocity deviations observed in a typical azimuthal scan are shown. Different histograms have been made for even and odd azimuths in order to separate velocity data measured at different PRFs.

The central peaks of Fig. 1, containing the points with hardly any deviation from the local median velocity, go up to a number of about 12 500. The vast majority of the analyzed points obeys local continuity. From the width of the central peaks, the standard deviation of the high and low PRF velocities is determined to be $\bar{\sigma} = 0.50$ m/s. The sideband peaks correspond to the velocity outliers which are characteristic for the dual-PRF technique. The percentage of velocity outliers is 0.91% and 0.73% for the even and odd azimuths, respectively. The median deviation of the even azimuth sidebands is 20.9 m/s and that of the odd azimuth sidebands is 24.6 m/s. These velocity deviations roughly match the unambiguous intervals of the low PRF (20.0 m/s) and high PRF (26.6 m/s) measurements. This evidences that the outliers in dual-PRF velocity data are due to deliasing errors.

The origin of the dealiasing errors has been depicted schematically in Fig. 2. On the horizontal axis the deviation of the primary velocity estimate relative to the true value is given. The Gaussian curve represents the distribution of possible deviations of the primary velocities.

Because the primary velocity estimate is determined from two measurements (high and low PRF) at slightly different locations (1 degree apart), this estimate can be biased due to horizontal wind shear:

$$\Delta\tilde{V}_{lh}(\Delta V_s) = \begin{cases} (N+1)\Delta V_s & \text{for PRF}_h \\ -N\Delta V_s & \text{for PRF}_l \end{cases} \tag{4}$$

where ΔV_s is the radial velocity difference between the locations due to horizontal wind shear. Just as the standard deviation, the bias gets more pronounced for higher unfolding factors. When the primary dual-PRF velocity estimate is deviating more than the unambiguous velocity, the original velocity is assigned to an incorrect Nyquist interval. The fraction of dealiasing errors η, which is marked by the shaded area in Fig. 2, can be calculated:

$$\eta = \frac{1}{2}\left[\text{erfc}\left(\frac{V_h^u \pm \Delta\tilde{V}_{lh}}{\sqrt{2}\sigma_{lh}}\right) + \text{erfc}\left(\frac{V_l^u \pm \Delta\tilde{V}_{lh}}{\sqrt{2}\sigma_{lh}}\right)\right] \tag{5}$$

where erfc(x) is the complementary error function (Press et al., 1992) and the mean of the $+/-$ terms has to be used.

In Fig. 3 the fraction of outliers is plotted as a function of the standard deviation of the dealiased velocities for the set of 300 azimuthal scans (see Sect. 3). Both the fraction of outliers and the standard deviation of the dealiased velocities have been determined using the “histogram analysis” (see Fig. 1). The standard deviation of the original/dealiased velocities has been converted to that of the primary dual-PRF velocity estimates using the multiplication factor given by Eq. (3). The theoretical dependence as implied by Eq. (5) is plotted for three radial velocity differences. The majority of the experimental datapoints is grouped around the theoretical curve for a radial velocity difference of 1 m/s.

5 High quality velocity data

A three-step post-processing algorithm is proposed for the production of high quality dual-PRF velocity data, i.e., with less than 0.1% outliers. This algorithm is intended for real-time operational use and will be implemented at KNMI in the near future.

5.1 Group-size filtering

During the first step, "noise" from non-hydrometeor scatterers at short ranges and clutter not eliminated by the Doppler filtering are removed from the dual-PRF data by digital filtering. A group is defined as a collection of range bins containing valid data, which will be referred to as datapoints, that are connected in radial and/or azimuthal direction. The groups are identified using an efficient labeling technique described by Gonzalez and Woods (1992) and a ready algorithm for sorting labels into equivalent classes (Press et al., 1992). The number of datapoints and "zero-velocity" points per group are counted. Groups consisting of less than a certain minimum number of datapoints are removed entirely from the azimuthal scan. The minimum group size is 25 at zero range, and it gradually decreases to 10 at 150 km range. Up to a range of about 25 km, groups containing more zero-velocity points than other points are removed entirely from the azimuthal scan as well. After filtering, the minimum size of groups of connected datapoints is known which will be used later on.

5.2 Global dealiasing

The global dealiasing, which is the second step, usually has no effect on the data, but is designed to restore large scale dealiasing errors. Velocities outside of the extended unambiguous interval, which is 40 m/s in our case, cannot be dealiased correctly by the dual-PRF technique. For dual-PRF data, however, large scale dealiasing errors are less likely to occur because of the extended unambiguous velocity interval. Taking into account the large unambiguous interval of the dual-PRF data, a rather straightforward dealiasing method based on an environmental wind profile is adopted. Velocities are dealiased by adding a multiple of $2V_{lh}^{u}$ ($\simeq 80$ m/s) minimizing the difference with the environmental wind (Hennington, 1981). An upper-air sounding or a model profile can be used as the environmental profile, but the use of a radar wind profile is preferred. Aliasing errors are generally no problem in these radar wind profiles, because they are usually recorded with higher PRFs and most profile algorithms are rather insensitive to isolated dealiasing errors.

5.3 Local dealiasing

In the final step, local dealiasing errors are identified using the local median velocity and corrected by adding or subtracting multiples of twice the high or low unambiguous velocity. The calculation of the local median velocity is based on at least nine valid datapoints. When the nine valid datapoints are not present in a 3×3 polar kernel, the kernel is enlarged step by step until they can be collected. The "adaptive" local median velocity can be determined for each datapoint in this way, since the minimum number of connected datapoints per group has been set by the group-size filtering. Datapoints deviating more than the unambiguous velocity from the local median velocity are considered outliers and are corrected. This correction method retains the spatial res-

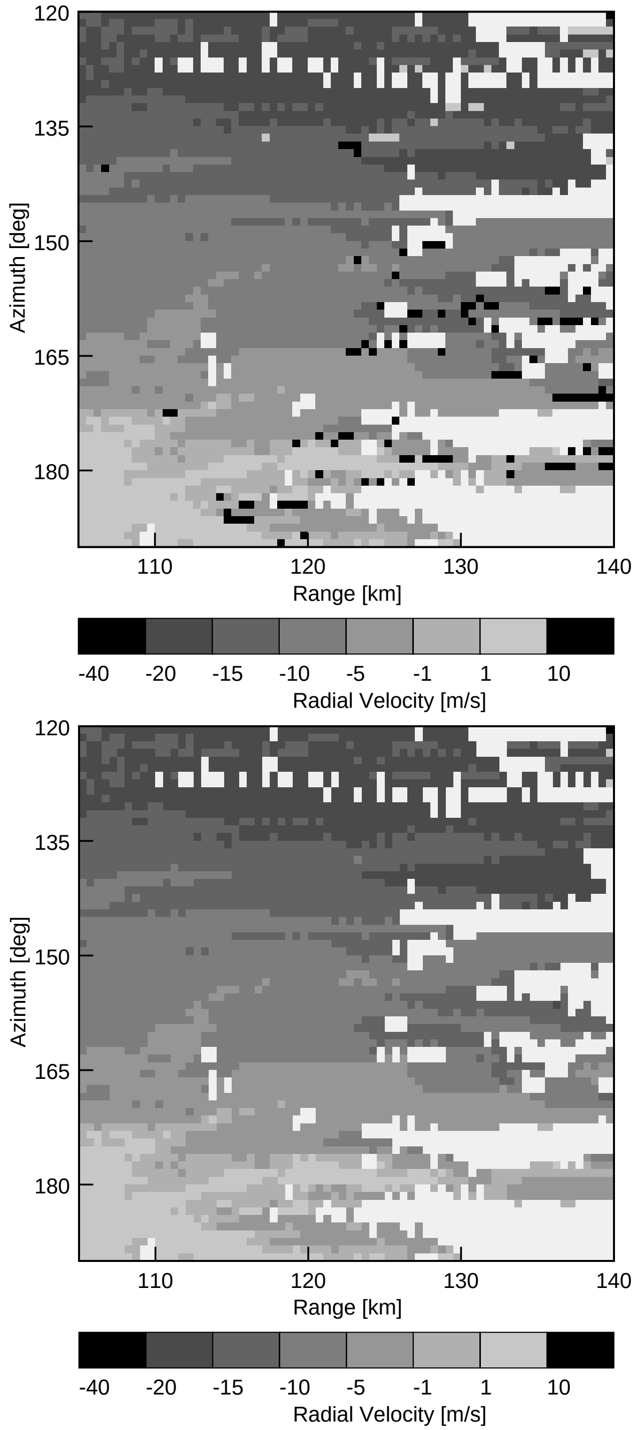

Fig. 4. Example of raw and processed dual-PRF velocity data from 14:45 UTC 7 November 2001. The left frame shows a part of the raw azimuthal scan data and the right frame shows the same data after group-size filtering and a single pass of the local dealiasing algorithm. Black is used to highlight the outliers.

Table 1. The percentage of high-quality scans, i.e., with less than 0.1% outliers, are considered. The results for the raw scans, the group-size filtered scans, and the corrected scans after one, two, and three pass(es) of local dealiasing algorithm are listed

	raw	filter	1st pass	2nd pass	3rd pass
$\eta \leq 0.1\%$	3.5%	4.2%	89.5%	99.3%	99.7%

olution of the velocity data, and it is very efficient because the local median velocity is determined from nine valid datapoints thus allowing up to four nearby outliers.

5.4 Results

In Fig. 4 an example of raw and processed dual-PRF velocity data is shown. This azimuthal scan has been recorded while a cold front was moving from west to east across the Netherlands. A part of the scan with a relatively high concentration of dealiasing errors and numerous voids in the velocity data is depicted. The left frame shows the raw velocity data and the right frame shows the same data after group-size filtering and a single pass of the local dealiasing algorithm. It is evident that all velocity outliers are corrected by the post-processing algorithm without affecting the (main) velocity gradients.

The algorithm has been applied to the set of 300 azimuthal scans (see Sect. 3). The percentage of high-quality scans, i.e., azimuthal scans with less than 0.1% outliers, has been monitored. The results are given in Table 1. The global dealiasing step has been skipped because the maximum wind speed in the set of azimuthal scans is considerably lower than the extended unambiguous velocity. The first pass of the local dealiasing algorithm increases the percentage of high-quality scans from 4% to roughly 90%. After the second pass, the percentage of high-quality scans is already approaching 100%.

Dealiasing of velocities with the dual-PRF technique is inherently difficult in areas with high wind shear or strong turbulence (large standard deviation). Using the proposed algorithm, the resulting artifacts, i.e., isolated dealiasing errors, can be corrected to a large extent. It is the subject of further study to find the meteorological limits of the dual-PRF technique and this correction algorithm.

6 Conclusions

Radial velocity data obtained using the dual-PRF technique have been analyzed quantitatively. The analyzes confirm that the velocity outliers are in fact isolated dealiasing errors. A simple model has been employed to describe the dependence of the fraction of dealiasing errors on the standard deviation of the velocity estimates and the azimuthal shear of the radial wind component.

A post-processing algorithm for the production of high quality velocity data is proposed. This three-step algorithm removes noise from nearby non-hydrometeor scatterers and corrects dealiasing errors, and it is intended for operational use. The spatial resolution of the velocity data is retained, because no smoothing is performed. Preliminary results on the performance of the algorithm have been obtained by processing of a set of 300 azimuthal scans. About 90% of the azimuthal scans is upgraded to high quality by group-size filtering and a single pass of the local dealiasing algorithm. The post-processing algorithm for dual-PRF velocity data will be implemented at KNMI and is expected to enable further development of Doppler radar applications, like wind shear detection, dual-Doppler wind fields, and assimilation into NWP models.

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