A Velocity Dealiasing Technique Using Rapidly Updated Analysis from a Four-Dimensional Variational Doppler Radar Data Assimilation System

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ABSTRACT

A Doppler velocity dealiasing algorithm is developed within the storm-scale four-dimensional radar data assimilation system known as the Variational Doppler Radar Analysis System (VDRAS). The innovative aspect of the algorithm is that it dealiases Doppler velocity at each grid point independently by using three-dimensional wind fields obtained either from an objective analysis using conventional observations and mesoscale model output or from a rapidly updated analysis of VDRAS that assimilates radar data. This algorithm consists of three steps: preserving horizontal shear, global dealiasing using reference wind from the objective analysis or the VDRAS analysis, and local dealiasing. It is automated and intended to be used operationally for radar data assimilation using numerical weather prediction models.

The algorithm was tested with 384 volumes of radar data observed from the Next Generation Weather Radar (NEXRAD) for a severe thunderstorm that occurred during 15 June 2002. It showed that the algorithm was effective in dealiasing large areas of aliased velocities when the wind from the objective analysis was used as the reference and that more accurate dealiasing was achieved by using the continuously cycled VDRAS analysis.

1. Introduction

Doppler weather radar data have been used extensively in many meteorological applications, such as detection and nowcasting of hazardous weather and quantitative rainfall forecasting using advanced data assimilation techniques that involve numerical forecast models. Doppler velocity, commonly called radial velocity, has a crucial role in data assimilation for improvement of the quantitative prediction of precipitation (Sun and Crook 1997; Sun 2005a; Xiao et al. 2007). One of the long-standing issues in the use of radar radial velocity for various applications is the data quality control of aliased velocities, known as velocity dealiasing.

Radial velocity is aliased when the true radial velocity is larger than the unambiguous velocity of a radar or Nyquist velocity (v\text{\textsubscript{N}}; Doviak and Zrnić 1993). Radial velocity is calculated based on the phase shift between the signals that are transmitted from the radar and returned by moving particles. The maximum phase shift discerned by radar is determined by the pulse repetition frequency (PRF) of the radar at a specific wavelength. To increase the magnitude of the unambiguous velocity, one must increase the PRF. However, because the unambiguous maximum range \( r_a \) of radar observation is inversely proportional to the PRF, a coupling relationship between these two variables, \( r_a \text{PRF} = c\lambda/8 \), where \( c \) and \( \lambda \) stand for the speed of light and the wavelength of a radar, is obtained and thus resulted in a trade-off between the two variables. That is, to have a reasonable unambiguous range the Nyquist velocity has to be limited.

Many researchers developed algorithms in the past to dealias radar velocities. The algorithms can be categorized in two groups: the continuity check and the reference check. The first continuity check algorithm (Ray and Ziegler 1977) was performed one-dimensionally (1D) only in the radial
direction. It was effective only when atmospheric flows were quasi-uniformly distributed around the mean or could be adjusted to quasi-uniform distribution. It also worked only when radial velocities were aliased once. Bargen and Brown (1980) also suggested a 1D algorithm by assuming that the first gate in each radial was free of error, which was not guaranteed, especially for strong wind shear zones such as hurricanes, gust fronts, etc. Merritt (1984) introduced a two-dimensional (2D) continuity check in both radial and azimuth directions. He segmented a sweep into regions having similar velocities, which were in the range of the percent of the Nyquist velocity. Then, he determined the appropriate dealiasing number for each region by minimizing the shear across the boundary of adjacent regions. This technique was later further extended to a three-dimensional (3D) algorithm by Bergen and Albers (1988). The methods based on a continuity check tended to have problems in regions of strong shear because aliased data were sometimes incorrectly grouped with data that were not aliased, causing incorrect dealiasing.

Because the radial velocity field alone cannot dealias the velocity effectively, additional environmental wind information was introduced starting from Bargen and Brown (1980) and Henninger (1981). Eilts and Smith (1990) suggested using environmental sounding or velocity azimuth display (VAD; Browning and Waxler 1968) wind information to produce initial values for each elevation scan where there was not enough velocities to compare with, for example, in the region of isolated echoes. The algorithm was used during the real-time 1988 Terminal Doppler Weather Radar (TDWR) Operational Test Evaluation and showed its feasibility for operational use. Zhang and Wang (2004) enhanced a 2D continuity check algorithm using multiple passes to obtain more accurate and reliable reference velocities from radar velocities themselves for operational implementation. This technique was tested on data from a Weather Surveillance Radar-1988 Doppler (WSR-88D) located in Taiwan and three WSR-88Ds in the United States with a total of more than 1000 volumes. They reported that more than 99% of aliased velocities were successfully dealiased based on the examination by a human expert. James and Houze (2001) added two more dimensions of the vertical elevation and the time to the 2D dealiasing algorithms. Their technique examined one tilt angle at a time starting from the highest elevation where the clutter was minimal and gate-to-gate shear was typically low and then dealiased each tilt in descending order. The inclusion of the time dimension provided an additional constraint from the previously dealiased velocity field. They also used a wind profile, which came from either VAD or environmental sounding, to correct any remaining isolated echoes. The technique was applied to data from a C-band radar, which had low Nyquist velocity, during two months of the 1999 Mesoscale Alpine Program (MAP). They concluded that 93% of 4300 tilts were dealiased without error.

Most of the reference check algorithms use VAD profile because it is available whenever radial velocities are available. However, the wind profile from VAD is not always reliable, especially when the observed radial velocities are already aliased. Therefore, some techniques were developed to circumvent the problem by refining the derived VAD profile using multiple-step procedures (see Tabary et al. 2001; Gong et al. 2003) or the variational method (Gao et al. 2004).

Although the previously mentioned techniques for dealiasing radial velocity demonstrated some success in various applications, we found there was still a need to develop a more robust algorithm for the purpose of assimilating multiple operational radar observations into numerical models. We believe the main challenge for correctly dealiasing velocities, especially in a strong shear region and multiple-aliased area, from an operational network is to obtain high-resolution detailed reference wind. The reference wind from a nearby sounding of a conventional operation network is horizontally homogeneous and only updated every 12 h. The VAD profile calculated from radar is not always reliable and the horizontal resolution is not fine enough to represent the strong shear in some cases. Traditional analysis wind from a mesoscale model has better horizontal resolution than radiosonde observations but lacks the accuracy under severe weather conditions.

When a mesoscale model assimilates radar observations, it is able to provide more accurate and frequently updated finescale winds especially when storms exist (Sun and Crook 2001). These winds provide additional information and are good candidates for a 3D reference wind that can be used to perform velocity dealiasing. However, other procedures are still needed to ensure the quality of the dealiasing algorithm. In this study, we describe a dealiasing scheme for the Variational Doppler Radar Analysis System (VDRAS; Sun and Crook 1997, 1998); this scheme dealiases the radial velocity independently at each grid point by using the 3D wind from VDRAS as the reference wind. It performs the velocity dealiasing in three steps. First, the regions of real meteorological shear are masked so that the dealiasing will not be applied to these regions. This procedure is called “preserving horizontal shear”. Second, a global dealiasing is conducted using the VDRAS analysis wind at each grid point. The last step is to perform a local dealiasing by comparing the radial velocity wind with its neighboring grid points. Unlike the previous algorithms that are based on the continuity check, this scheme performs the
dealing at each grid point independently, using the high-resolution reference wind. Hence, it has less risk in producing large areas of incorrectly dealiased velocity, which is the most detrimental in terms of data assimilation applications. This paper is organized as follows. A brief description of VDRAS is presented in section 2. In section 3, the detailed dealiasing algorithm is described. In section 4, we describe results from an application of the algorithm to data from eight WSR-88D radars for a convective storm that occurred during International H2O Program (IHOP_2002). The IHOP_2002 field campaign was conducted in the southern Great Plains of the United States in early summer of 2002. The summary and conclusions are provided in the last section.

2. Description of VDRAS and the reference wind

VDRAS was designed to retrieve storm-scale dynamical, thermodynamical, and microphysical structures by assimilating time series of radar data from single or multiple radars using a four-dimensional variational technique (4DVar; Sun et al. 1991) and a cloud-scale numerical model. Usually an assimilation window of 12 min, which typically covers three volumes of data from each radar, is used for the 4DVar analysis. The system is continuously cycled with a short forecast of 5 min following each 4DVar assimilation cycle to provide a forecast background for the next cycle. As a result, VDRAS generates a new analysis every 17 min with this typical setup. The cloud model in VDRAS has six prognostic variables: the three velocity components ($u$, $v$, and $w$), liquid water potential temperature $\theta_l$, rainwater mixing ratio $q_r$, and total water mixing ratio $q_t$. The perturbation pressure $p$ and temperature $T$, water vapor mixing ratio $q_v$, and cloud water mixing ratio $q_c$ are diagnostic variables. The analyses of these prognostic variables are obtained by iteratively reducing a cost function defined by the discrepancy between the observed variables (radial velocity and reflectivity) and their model counterparts. The detailed description of the model, the cost function, and the 4DVar data assimilation procedure can be found in Sun and Crook (1997).

Because observations from each of the radars cover only a limited area, large data void regions exist in most operational radar networks. VDRAS uses a mesoscale background obtained by blending data from Weather Research and Forecasting (WRF; Skamarock et al. 2005) surface network and VAD (Lhermitte and Atlas 1961) profiles using a Barnes analysis technique (Barnes 1964) to serve as a first guess and background for the radar data assimilation. The mesoscale background analysis was first developed in the forecast demonstration project during the 2000 Sydney Olympics and described in Crook and Sun (2004). This mesoscale background is performed before the 4DVar radar data assimilation and updated at every assimilation cycle. The procedure of the analysis is given as follows:

1) Compute VAD profiles for each radar on VDRAS vertical grid.
2) Interpolate the model data to VDRAS vertical grid.
3) Blend the model data and the radar VAD profiles to produce a gridded analysis using a Barnes interpolation technique with a 50 km radius of influence.
4) Interpolate the surface observations horizontally to VDRAS grid using the Barnes interpolation scheme with a radius of influence of two times the average station spacing ($\sim$20 km).
5) A local linear least squares fit is applied vertically at each grid point to combine the surface analysis from 4) and the upper-air analysis from 3).

The mesoscale analysis obtained by the above procedure does not result in significant changes from the mesoscale model background, except for the lower levels because the VAD data and surface observations are only in the lower levels. The current operational mesoscale model systems do not provide a background field that has a close enough fit to observations at the low levels for the purpose of convective analysis and forecasting. The main reason is that these systems have an emphasis on obtaining better analyses and forecasts in the scales larger than the convective scale. Therefore, a modified background based on the frequently updated observations such as the VAD and surface data is necessary for better high-resolution low-level analysis and an improved reference wind for velocity dealiasing. Although this procedure is rather simple compared to a more sophisticated technique such as 3DVar, we believe it serves our purpose well in providing a more accurate first-guess field for the subsequent 4DVar radar data assimilation.

The flowchart in Fig. 1 shows the processes that contribute to the generation of the mesoscale background and the steps for velocity dealiasing. The modules, separated algorithms from VDRAS, above the black horizontal line perform data ingest and preprocessing. Radar data ingested to VDRAS are preprocessed from the radar spherical coordinates to a grid that has an even horizontal resolution. That is, on each constant-elevation-angle surface, data are interpolated from the original 2D polar-sampling grid to a 2D Cartesian grid with the grid increment of 1 km. This input data will be referred to as 1 km plane position indicator data (PPI). This preprocessing step has been used in VDRAS in the last several years, and its rationality was explained in Sun (2005b). Quality control procedures including the velocity dealiasing are applied to the 1 km PPI data. The noise removal for the radar data includes setting a threshold to get rid of any remaining
ground clutter, a generalized noise removal, and a filtering algorithm. Radial velocities smaller than 0.1 m s\(^{-1}\) are removed to eliminate ground-clutter contamination. The procedure is also effective in eliminating zero velocity rings that often exist at the edge of the radar coverage. A local variance is computed, and any data point with a variance of greater than 60.0 m\(^2\) s\(^{-2}\) is removed. A 3 × 3 grid filter that is based on a local least squares fitting method is then applied to remove high-frequency features that cannot be adequately represented by the model grid. Bergen and Albers (1988) pointed out that the filter could improve the dealiasing algorithm’s efficiency by a factor of 5 or more.

The reference wind \(U_e\) used for the velocity dealiasing comes either from the mesoscale background or from the latest VDRAS analysis including radar data; both are indicated by the heavy black rectangular boxes in Fig. 1. The wind from the mesoscale background is used whenever VDRAS has a “cold start,” which means a start-up cycle without VDRAS analysis (or forecast) from a previous cycle. When a data assimilation cycle is not a cold start, one can choose either the wind from mesoscale background or from the VDRAS analysis at the end of the previous 4DVar cycle. The velocity dealiasing algorithm (heavy dotted rectangular box) includes three steps, which are described in the next section. The dealiasing is performed before the 4DVar radar data assimilation. Consequently, the 4DVar analysis from the previous cycle has to be used for the dealiasing process in the current cycle if the 4DVar analysis is chosen to be the reference wind. After finishing velocity dealiasing, radial velocities are horizontally interpolated on to the VDRAS grid (4 km).

3. Description of the velocity dealiasing algorithm

The velocity dealiasing algorithm consists of three steps: preserving the horizontal gradient, global dealiasing, and local dealiasing. These steps are described in detail in the following. For a better understanding of the algorithm, we describe the global dealiasing before the preserving horizontal gradient, although in the actual execution of the algorithm the preserving horizontal gradient goes before the global dealiasing.

a. Global dealiasing

The global dealiasing attempts to correct the aliased velocity for the entire domain using the mesoscale wind or the 4DVar wind. VDRAS for this study is designed to cover an area that extends 460.0 km horizontally and
17.5 km vertically with 4-km horizontal and 500-m vertical resolutions. The time step for a 4DVar analysis is 10 s. The reference wind from VDRAS is on the Cartesian coordinates, whereas the input radar data to be dealiased are located on constant elevation angles with a 1-km increment. The reference wind is mapped to the radar data location using the nearest point assignment technique.

The procedure for the rectification of the aliased radial velocities is explained in the following. The true radial velocity $U$ can be expressed as

$$U = V + \kappa V_o$$

$$\kappa = \pm 0, \pm 1, \pm 2, \ldots, \tag{1}$$

where $V$ is the observed radial velocity that may have been aliased, $V_o = 2\nu$ is the ambiguous velocity interval, and $\kappa$ is the integer multiplier that is needed to remove Nyquist aliasing ambiguities from $V$. The nonzero integer factor $\kappa$ is determined by the difference between the measured radial velocity and the expected radial velocity $U_e$ at the radar data point. It can be approximated by

$$\kappa = \text{NINT} \left( \frac{U_e - V}{V_o} \right), \tag{2}$$

where NINT represents rounding off to the nearest integer. The expected radial velocity is obtained from the reference wind.

Figure 2 shows the radial velocity field on a 4.3° elevation angle for the KGLD radar located in Kansas at 1913 UTC 15 June 2002. There are two regions where the radial velocities are aliased, which are pointed by the two arrows in Fig. 2a. The blue area enclosed by the yellow colors shows the divergent winds caused by thunderstorm updraft. The size of the divergence area is less than 30 km in the shorter axis, which implies that the reference wind field has to be very detailed to avoid erroneous dealiasing.

b. Preserving horizontal gradient

The previously mentioned procedure should work well if the reference velocities at every grid point do not contain large errors. However, large errors often appear in regions associated with small-scale disturbances when the wind from the mesoscale background is used for dealiasing. Although radar data assimilation can significantly reduce these errors, it is still not guaranteed to produce a perfect reference velocity, especially in the regions of vigorous small-scale convection. Therefore, a procedure is developed to mask the region where strong horizontal shear is caused by true meteorological disturbance. For example, in a region of vigorous small-scale convection, the horizontal shear, which often results from the outflow of the convection itself, is very strong but confined in a small area. The signs of the radial velocities are changed at the boundary of the two adjacent regions: the small-scale disturbance region and the environmental flow region. The former boundary usually cannot be detected correctly by either mesoscale numerical model analysis or soundings. When winds used for dealiasing cannot represent the small-scale disturbance well, it is important to identify and exclude the regions where large errors may exist to prevent these regions from incorrect dealiasing.

To determine the region where radial velocities must not be dealiased with the VDRAS first-guess wind, the algorithm starts with assigning 0 as a flag at all grid points and then a multistep check is performed to identify the shear region. Whenever the grid point passes each criterion (step), number 1 is added. Figure 3 shows the result of the flag field after the procedure is applied to the radial velocity data shown in Fig. 2a. The first step is to detect the boundaries where the signs of the radial velocities are changed. A search is done in the four directions: eastward, westward, southward, and northward. Whenever the signs of two adjacent grid points reverse, a value of 1 is assigned to both points. This detects not only the shear boundary but also the boundary where velocities are aliased. The second step is to discriminate the shear boundary from the boundary of aliased velocities by selecting grid points where the absolute value of the radial velocity difference between the two adjacent grid points is smaller than 80% of the Nyquist velocity. This criterion is based on the fact that the velocity boundary caused by true meteorological disturbance always exhibits spatial continuity (i.e., a gradual transition from positive to negative values) resulting in smaller shear values, whereas the shear caused by the aliased velocity is greater than the Nyquist velocity. The different characteristics of the two boundaries are clearly shown in Fig. 2a. The light-gray boundary in Fig. 3 is the boundary caused by the aliased velocities as shown in Fig. 2a. The dark-gray boundary in Fig. 3 is also assigned value 1 after the first step but assigned value 2 after the second step. The third step is to determine whether the shear region is confined. If the number of grid points between the boundary points (with value 2) are smaller than 50 (=50 km for this study, empirical value), value 3 is assigned. As a result, the grid points in the white area are identified as the region that should not apply the global dealiasing.

Figure 2b shows the results of the global dealiasing using the first-guess mesoscale background wind when the procedure to preserve the horizontal shear is not applied. It is clearly seen that the region, enclosed by the dotted line, is incorrectly dealiased. Figure 2c shows the result of the global dealiasing after the preserving horizontal shear procedure is applied. It is clearly shown that the velocity values in the region of the convective flow are unaltered.
Note that the output from VDRAS (Figs. 2b, c, and d) has a horizontal resolution of 4 km, whereas the input data (Fig. 2a) ingested into VDRAS has a resolution of 1 km.

**c. Local dealiasing**

After the global dealiasing, a local dealiasing is performed based on the same concept as the global dealiasing but using a different reference wind. The local dealiasing procedure follows that of Miller et al. (1986). The reference wind is calculated using the observed radial velocities after the global dealiasing. At each grid point, an average radial velocity within a specified geometrical window is calculated. This reference velocity is used in Eq. (2) to compute \( \kappa \). If \( \kappa \) is not zero, a dealiasing is performed using Eq. (1). This procedure is repeated for six iterations corresponding to six different window sizes, which are defined by the number of grid points: 36, 49, 64, 81, 100, and 225, respectively. The size of the window is set in an increasing order because it is easier to obtain reliable radial velocity in a smaller window and dealiased velocity can then help provide a more reliable reference velocity in the larger window. When calculating
the averaged radial velocity, nonmissing data have to be available in all four quadrants, and the number of data points must exceed 80% of the total grid points in the window. If the criteria are not satisfied, the radial velocity at the center of the window is not dealiased. The dealiased velocity after the local dealiasing is shown in Fig. 2d. Comparing Fig. 2d with Fig. 2c, it is seen that the area in the dotted circle in Fig. 2c is dealiased in Fig. 2d.

4. Dealiasing experiments and their results

The dealiasing algorithm described previously was tested on the data of a convective system collected during IHOP_2002 from eight radars—the period is 1800–2200 UTC 15 June 2002. The eight radars are KAMA, KDDC, KFDR, KGLD, KICT, KINX, KTLX, and KVNX. The total number of volumes is 384 and the number of tilts is 3358. Two experiments were performed. In the first experiment, the radar radial velocities were dealiased using the mesoscale background as the reference wind. VDRAS was run continuously for the 4 h with all cold start every 5 min to produce the mesoscale analysis. Note that the mesoscale analysis is obtained using a Barnes objective analysis technique that combines a WRF model forecast (10 km horizontal resolution) closest to the analysis time, surface observations, and VAD profiles from the eight radars. In this experiment, the 4DVar radar data assimilation loop is turned off. In the second experiment, VDRAS was run in a similar manner but with the radar data assimilation loop turned on. So the reference wind used in the second experiments is the VDRAS analysis resulting from the radar data assimilation from the previous analysis cycle. The two experiments are summarized as follows:

(i) experiment 1: Cold-start cycles with no 4DVar radar data assimilation; mesoscale background wind is used as the reference wind; and

(ii) experiment 2: Continuous cycles with 4DVar radar data assimilation; VDRAS analysis from the previous cycle is used as the reference wind for the dealiasing and background field (or first guess) for the assimilation in the current cycle.

Table 1 gives a summary of the dealiasing performance based on a subjective evaluation. The number of tilts that is either not dealiased or incorrectly dealiased is shown in the last two columns. The result from the experiment in which the reference wind from the mesoscale background is used is shown in the third column and from the 4DVar analysis in the fourth column. Among the 3358 tilts, more than one-third contain aliased velocities, and some of them are multiple aliased. After the global dealiasing using the mesoscale background wind and the local dealiasing, aliased velocities remain in 196 tilts, which is 5.8% of the total number of tilts. When the 4DVar wind is used as the reference wind, only 89 tilts (2.6%) are not dealiased properly. Because the automated dealiasing algorithm may erroneously modify velocities that are correctly observed, these percentages are calculated based on the total number of tilts instead of only the tilts that contain aliased velocities. We have found that the algorithm works for both single- and multiple-aliased velocities. The remaining bad velocities are rejected in the data assimilation process by setting the criterion that the absolute value of the difference between the observed radial velocity and
the model counterpart is larger than 5 m s$^{-1}$. We found that the rejection of these velocities have negligible impact on the data assimilation results because the remaining aliased data are usually in very small areas.

Figure 4 shows an example in which both experiments work successfully in correcting aliased velocity. The aliased radial velocities in the northwest corner on the 3.3° elevation angle from KICT radar (Fig. 4a) are correctly dealiased by both the mesoscale background wind (Fig. 4b) and the 4DVar wind (Fig. 4c). Note that Figs. 4b and 4c show the dealiased radial velocity after it is interpolated to the VDRAS analysis grid (4 km resolution), whereas the observed radial velocity (Fig. 4a) is shown with the resolution of 1 km. The wind vectors on the model level of 10.75 km above ground level are drawn to approximately match the height at the location of the aliased radial velocities.
The wind direction in the region of the aliased velocities is westerly in Fig. 4b. The radial velocity projected on the radar beam is toward the radar. The mesoscale background wind is accurate enough to correct the aliased wind. At the same region, the 4DVar wind shows a slight disturbance but maintains its major westerly component.

As discussed in the previous section, the preserve-horizontal-shear procedure is necessary to prevent the algorithm from incorrectly dealiasing real perturbed velocities associated with convection. This procedure works well in most cases but may fail when the perturbed velocities are not bounded; in which case, an accurate reference wind becomes critical for the dealiasing algorithm to work successfully. Figure 5 shows an example in which the algorithm incorrectly changed the observed negative velocity (Fig. 5a) to positive when the mesoscale wind is used as the reference wind (Fig. 5b) but worked successfully when the 4DVar wind is used (Fig. 5c). The
reference wind on 8.75 km is overlaid in Figs. 5b and 5c. Note that the radial velocity shown in the figure is for the 5.2° elevation angle while the wind vectors are from the model level of 8.75 km. It is, therefore, not surprising that the two do not match at every grid point in terms of the radial wind component. The failure of the dealiasing with the mesoscale wind is caused by two factors: it cannot capture the divergent flow at the high level caused by a convective storm and the preserving horizontal gradient procedure failed to mask the area because it is not bounded. The success with the 4DVar wind is clearly attributed to the more accurate wind in the convective region.

For some tilts, the mesoscale background wind corrects most of the aliased velocity data in the first experiment, whereas the VDRAS analysis wind successfully corrects all the aliased velocity in the second experiment. Figure 6 shows an example in which most of the aliased velocities are corrected with the mesoscale wind (Fig. 6b), leaving...
only a small area (the blue enclosed by the red near the center of the domain) that is not dealiased. When the 4DVar wind is used, the entire tilt is dealiased successfully (Fig. 6c).

As indicated by Table 1, even when the 4DVar wind is used as the reference wind, 2.6% of the tilts are not dealiased perfectly. However, it is found that the size of the area in which the velocities remain aliased or incorrectly modified is reduced in experiment 2 as compared with experiment 1. Figure 7 shows an example of this. In Fig. 7c, the red color area along the southeast data boundary indicates the velocities are incorrectly modified, but the size of the area shrinks compared with that in Fig. 7b. These bad data are easily rejected by a criterion that compares the difference between the observed radial velocity and the radial velocity calculated from the background field. It is worth noting that for Figs. 5, 6, and 7 we have deliberately chosen examples in which the velocity dealiasing...
does not work very well in experiment 1 but is improved in experiment 2. As shown by the statistics in Table 1, for most of the tilts both experiments work equally well.

5. Summary and conclusions

An algorithm for dealiasing radial velocities in the data assimilation system VDRAS is presented. The innovative aspect of the algorithm is that it dealiases Doppler velocity at each grid point independently by using 3D wind fields obtained either from an objective analysis using conventional observations and mesoscale model output or from rapidly updated 4DVar analysis of VDRAS that assimilates radar data. This algorithm consists of three steps: preserving wind shear, global dealiasing using reference wind from the objective analysis or the 4DVar analysis, and local dealiasing. The algorithm is performed inside of VDRAS. Because this algorithm performs the dealiasing at each grid point independently using the high-resolution reference wind, it has less risk in producing large areas of incorrectly dealiased velocity, which is desirable for data assimilation purposes. The algorithm was tested with 384 volumes of radar data observed from the Next Generation Weather Radar (NEXRAD) for a severe thunderstorm that occurred during 15 June 2002. There were two experiments conducted. The first used the mesoscale background wind, constructed by the objective analysis using mesoscale model output, surface observations, and VAD analysis with cold-start cycles as the reference wind. The second used the VDRAS 4DVar analysis wind produced by running in the cycling mode and assimilating radar data continuously. It was shown that the algorithm was effective in dealiasing large areas of aliased velocities when the wind from the objective analysis was used as the reference wind and more accurate dealiasing was achieved by using the continuously cycled VDRAS analysis. The VDRAS 4DVar analysis with radar data assimilation provided more detailed wind structure than the mesoscale background wind and hence resulted in better dealiased radial velocity field.

The algorithm also includes three other procedures that are not discussed in this paper. One is a vertical consistency check and another is a recalculation of the VAD analysis after the dealiasing. The modified VAD analysis can help get better mesoscale background wind. The last is to correct the location of a forecasted typhoon center using observation when the background field is constructed by WRF. These three procedures were not used in the current study and therefore were not discussed in the paper. These procedures may be helpful in some weather situations, for instance, hurricanes. The next step is to run VDRAS with the new dealiasing algorithm in real time to evaluate its operational performance.

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