An IVAP-Based Dealiasing Method for Radar Velocity Data Quality Control

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ABSTRACT

Dealiasing is a common procedure in radar radial velocity quality control. Generally, there are two dealiasing steps: a continuity check and a reference check. In this paper, a modified version that uses azimuthal variance of radial velocity is introduced based on the integrating velocity–azimuth process (IVAP) method, referred to as the V-IVAP method. The new method can retrieve the averaged winds within a local area instead of averaged wind within a full range circle by the velocity–azimuth display (VAD) or the modified VAD method. The V-IVAP method is insensitive to the alias of the velocity, and provides a better way to produce reference velocities for a reference check. Instead of a continuity check, we use the IVAP method for a fine reference check because of its high-frequency filtering function. Then a dealiasing procedure with two steps of reference check is developed. The performance of the automatic dealiasing procedure is demonstrated by retrieving the wind field of a tornado. Using the dealiased radar velocities, the retrieved winds reveal a clear mesoscale vortex. A test based on radar network observations also has shown that the two-step dealiasing procedure based on V-IVAP and IVAP methods is reliable.

1. Introduction

From pulsed radars, the radial wind velocity is obtained by the Doppler frequency shift of the pulses. Determined by the pulse repetition frequency, there is an upper limit of the velocity that can be directly observed (Doviak and Zrnić 1993). The maximum velocity is called Nyquist velocity V_r^N , and the radial velocities beyond that are aliased back into the Nyquist interval between $[-V_r^N, V_r^N]$. Therefore, the true value of radial velocity at each point V_r^t can be expressed by raw observation V_r and the Nyquist velocity using

$$V_r^t = V_r - 2nV_r^N, \quad (1)$$

where the folding number n is an integer ($\dots, -2, -1, 0, 1, 2, \dots$). When $n = 0$, the true value is equal to the observed one. Quality control should be done to determine the folding number, and to obtain the true value of the radial velocity, which is the dealiasing process.

As shown in Eq. (1), n is an integer, and the aliased radar radial velocity usually can be determined by abrupt velocity change about $2V_r^N$ between neighboring measurements. Various techniques to correct aliased velocities have been developed (Eilts and Smith 1990; Jing and Wiener 1993; Yamada and Chong 1999; James and Houze 2001; Tabary et al. 2001; Gong et al. 2003; Gao et al. 2004; Haase and Landelius 2004; Zhang and Wang 2006; Zhu and Gong 2006; Xu et al. 2010, 2011). The basic idea is that the change of velocity should be continuous if alias does not exist. The dealiasing

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FIG. 1. (a) Simulated original velocities (solid line) with aliased velocities (dotted line) and (b)–(f) retrieved radial velocities using V-IVAP method with retrieval sector sizes of $[\theta - 90^\circ, \theta + 90^\circ]$, $[\theta - 45^\circ, \theta + 45^\circ]$, $[\theta - 20^\circ, \theta + 20^\circ]$, $[\theta - 10^\circ, \theta + 10^\circ]$, and $[\theta - 5^\circ, \theta + 5^\circ]$, respectively.

methods are various ways of searching for the abrupt velocity change and then determining the folding number n .

Equation (1) also shows that every velocity might be aliased, because the continuous change of velocity means the folding numbers of the velocities are the same; it does not imply that the folding numbers are zero. Therefore, correcting aliased velocities requires additional independent wind information to provide some reference points. There are studies focused on this issue (Ray and Ziegler 1977; Bergen and Brown 1980; Hennington 1981; Bergen and Albers 1988; Gao et al. 2004; Xu et al. 2010). Some of these studies used full wind retrieval methods to obtain the reference. For example, Gong et al. (2003) applied the modified velocity–azimuth display (VAD) method (Tabary et al. 2001) to produce the reference velocity. The advantages of this method are (i) the reference velocities are from the radar data themselves and require no addition data, and (ii) the modified VAD method is insensitive to the alias of the velocity. Gao et al. (2004) improved the modified VAD method by introducing a new way to calculate the velocity gradient. Xu et al. (2011) upgraded the

VAD-based dealiasing method by using the alias-robust VAD algorithm (Xu et al. 2010) to obtain the reference velocities by fitting the VAD wind model to aliased raw radial velocities directly.

The aforementioned methods for dealiasing fall into two groups: continuity check and reference check. Generally, these two groups are implemented in two steps of a complete dealiasing procedure. The first step of reference check corrects some aliased velocities, when their references are available. Then the dealiased velocities are used as the start of continuity check in the second step. The radiosondes, wind profiler observations, numerical model forecasts, VAD (or modified VAD) retrieved winds, etc., can all be used as references. The modified VAD method is a reliable method to provide reference velocities. However, the modified VAD method can only give the averaged velocity at the center of the range circle (vertical wind profile at the location of the radar). When the wind changes sharply, the reference would have large difference from the observed velocity, especially when the radius of the range circle is large. On the other hand, the VAD (same for modified VAD) method does not work if partial

FIG. 2. (a) Raw radar velocity data (shading) and (b) dealiased velocity (shading) of Yancheng radar on the tilt with an elevation angle of 5.93° according to the retrieved velocity [contours in (a) and (b)] using the V-IVAP method.

observations are missing along the range circle. In [Gong et al. \(2003\)](#), the range circle was selected to perform modified VAD retrieval only if 55% of the full range circle (360°) was covered by raw data. In this study, a modified integrating velocity–azimuth process (IVAP) method is proposed based on the original IVAP method ([Liang 2007](#)), which can retrieve averaged full winds within a local area using the radar velocity data within that area instead of the averaged full winds within the full range circle by the VAD (or modified VAD) method. The new method is insensitive to aliasing of velocities; thus, it is used to produce reference velocities for reference check.

The main idea of continuity check is to find the disrupt change of velocity between neighboring points. In the IVAP method, the disrupt change of velocity can be determined by the large difference between retrieved velocity and the observed one. Then multiscale IVAP retrieving processes are applied for fine reference check instead of gate-to-gate continuity check in this study. Together, the two-step dealiasing procedure is developed, and tested by using a tornado case and data from a radar network. The modified IVAP method is described in [section 2](#). The two-step dealiasing

procedure is introduced in [section 3](#), followed by case studies in [section 4](#). Conclusions and discussion are given in [section 5](#).

2. IVAP technique and modification

To retrieve the full wind based on single-radar radial velocity observations, the VAD method was proposed ([Lhermitte and Atlas 1961](#); [Browning and Wexler 1968](#)) by assuming the wind field varies linearly. Given the radar-observed radial velocity

$$V_r = u \cos\phi \sin\theta + v \cos\phi \cos\theta + (w - w_t) \sin\phi, \quad (2)$$

where V_r is radar radial velocity, (u, v, w) are the three components of the full wind, θ is the azimuth angle of radar scan, ϕ is the elevation angle, and w_t is the terminal fall velocity of the raindrop. The VAD method can retrieve the mean wind and other kinematic information within the range circle. To obtain the local mean wind, the uniform wind (UW) method ([Persson and Andersson 1987](#)) and velocity–azimuth process (VAP) method ([Tao 1992](#)) were proposed. These methods can be used to obtain mean winds in a given small azimuthal

FIG. 3. As in Fig. 1, but using the IVAP method.

sector along the range circle. Liang (2007) demonstrated that the VAD, VAP, and UW methods can be combined into one form (the IVAP method) to retrieve the mean wind within a given azimuthal sector (range from 1° to 360°). The IVAP method retrieves the mean wind ($\bar{u}$, $\bar{v}$) by solving the following equations:

$$\begin{aligned} \sum_{\Omega} V_r \sin \theta &= \bar{u} \sum_{\Omega} \sin^2 \theta \cos \phi + \bar{v} \sum_{\Omega} \sin \theta \cos \theta \cos \phi, \\ \sum_{\Omega} V_r \cos \theta &= \bar{u} \sum_{\Omega} \sin \theta \cos \theta \cos \phi + \bar{v} \sum_{\Omega} \cos^2 \theta \cos \phi, \end{aligned} \quad (3)$$

where Ω is a given size of sector. In Liang (2007), the given sector is a range of azimuth angles. As mentioned by Chen et al. (2017), the given sector Ω can be any shape, such as a rectangle or a cube in the longitude–latitude coordinates, or their corresponding shapes in radar coordinates. As shown in Liang (2007), this method has a high-frequency filtering function. It is insensitive to high-frequency noise in the raw data. The high-frequency filtering function can be used in continuity check, because the alias of velocities is usually connected to disrupted changes (of high frequency) around the Nyquist velocity.

One of the advantages of the IVAP method is local wind retrieval, instead of full circle mean wind retrieval

by the VAD method. However, the IVAP method is sensitive to aliased velocity. It is not reliable for producing reference wind. Following the same idea of the modified VAD method (Tabary et al. 2001), Eq. (2) can be changed to

$$\begin{aligned} V_{r,\theta_1} - V_{r,\theta_2} &= u_{\theta_1} \cos \phi \sin \theta_1 - u_{\theta_2} \cos \phi \sin \theta_2 \\ &\quad + v_{\theta_1} \cos \phi \cos \theta_1 - v_{\theta_2} \cos \phi \cos \theta_2 \\ &\quad + (w_{\theta_1} - w_{t,\theta_1}) \sin \phi - (w_{\theta_2} - w_{t,\theta_2}) \sin \phi, \end{aligned} \quad (4)$$

where θ_1 and θ_2 are two neighboring azimuth angles along a radius r . Replacing $(u_{\theta_1}, v_{\theta_1}, w_{\theta_1}, w_{t,\theta_1})$ and $(u_{\theta_2}, v_{\theta_2}, w_{\theta_2}, w_{t,\theta_2})$ with the mean winds ($\bar{u}$, $\bar{v}$, $\bar{w}$, $\bar{w}_t$) within the sector $[\theta_1, \theta_2]$ gives us

$$\begin{aligned} V_{r,\theta_1} - V_{r,\theta_2} &= \bar{u}(\cos \phi \sin \theta_1 - \cos \phi \sin \theta_2) \\ &\quad + \bar{v}(\cos \phi \cos \theta_1 - \cos \phi \cos \theta_2) \\ &\quad + (\bar{w} - \bar{w}_t)(\sin \phi - \sin \phi). \end{aligned} \quad (5)$$

Given $\theta_2 = \theta_1 - \Delta\theta$ for convenience, Eq. (5) changes to

$$\begin{aligned} V_{r,\theta} - V_{r,\theta-\Delta\theta} &= \bar{u}[\cos \phi \sin \theta - \cos \phi \sin(\theta - \Delta\theta)] \\ &\quad + \bar{v}[\cos \phi \cos \theta - \cos \phi \cos(\theta - \Delta\theta)]. \end{aligned} \quad (6)$$

FIG. 4. Flowchart of the two-step dealiasing procedure.

In this study, we use $\Delta\theta = 1^\circ$. Then the IVAP method in Eqs. (3) becomes

$$\begin{aligned}
 \sum_{\Omega} (V_{r,\theta} - V_{r,\theta-\Delta\theta}) [\sin\theta - \sin(\theta - \Delta\theta)] &= \bar{u} \sum_{\Omega} [\sin\theta - \sin(\theta - \Delta\theta)]^2 \cos\phi \\
 &\quad + \bar{v} \sum_{\Omega} [\sin\theta - \sin(\theta - \Delta\theta)] [\cos\theta - \cos(\theta - \Delta\theta)] \cos\phi, \\
 \sum_{\Omega} (V_{r,\theta} - V_{r,\theta-\Delta\theta}) [\cos\theta - \cos(\theta - \Delta\theta)] &= \bar{u} \sum_{\Omega} [\sin\theta - \sin(\theta - \Delta\theta)] [\cos\theta - \cos(\theta - \Delta\theta)] \cos\phi \\
 &\quad + \bar{v} \sum_{\Omega} [\cos\theta - \cos(\theta - \Delta\theta)]^2 \cos\phi.
 \end{aligned} \tag{7}$$

FIG. 5. The locations of Yancheng (YC), Liangyungang (LY), and Huaian (HA) radars with a mosaic of reflectivity at the 3000-m level (shading). The location of the tornado is indicated by an open circle and letter T.

This modified IVAP method has the same advantages of the modified VAD; that is, it is insensitive to alias of radial velocities. Furthermore, this method is insensitive to vertical motion when assuming uniform vertical motion in a given area Ω . If the folding number n_θ and $n_{\theta-\Delta\theta}$ are the same, the value of $V_{r,\theta} - V_{r,\theta-\Delta\theta}$ is not affected by velocity alias because

$$\begin{aligned} & (V_{r,\theta} - 2n_\theta V_r^N) - (V_{r,\theta-\Delta\theta} - 2n_{\theta-\Delta\theta} V_r^N) \\ &= (V_{r,\theta} - V_{r,\theta-\Delta\theta}) - (2n_\theta V_r^N - 2n_{\theta-\Delta\theta} V_r^N) \\ &= V_{r,\theta} - V_{r,\theta-\Delta\theta}. \end{aligned} \quad (8)$$

When n_θ and $n_{\theta-\Delta\theta}$ are different (jump of folding number between neighboring points), the value of $V_{r,\theta} - V_{r,\theta-\Delta\theta}$ should be very large ($\sim 2V_r^N$). The disrupted

change of wind velocities can be avoided by omitting the large value of $V_{r,\theta} - V_{r,\theta-\Delta\theta}$ (in this study, the value is omitted when it is bigger than the Nyquist speed) caused by the jump of the folding numbers. Because the modified IVAP method uses azimuthal variance of radial velocities instead of velocity itself as in the IVAP method, this modified IVAP method is named the V-IVAP (azimuthal-variance form of the IVAP) method. Because the V-IVAP method is insensitive to alias of velocities, it can be used to produce reference velocities during reference check. The performance of the V-IVAP method will be shown next.

3. Combining two forms of IVAP in a two-step dealiasing procedure

Here, the functions of the two-step procedure are shown using two idealized examples. In these examples, the radar radial velocities are simulated using a uniform wind field with $u = 18 \text{ m s}^{-1}$ and $v = 5 \text{ m s}^{-1}$. The Nyquist velocity is set to 18 m s^{-1} . A random noise with maximum amplitude of 1 m s^{-1} is introduced in every simulated radial velocity. The V-IVAP method of Eq. (7) is applied to retrieve the winds at each point (with azimuth angle θ) over five difference azimuth angle sectors of $[\theta - 90^\circ, \theta + 90^\circ]$, $[\theta - 45^\circ, \theta + 45^\circ]$, $[\theta - 20^\circ, \theta + 20^\circ]$, $[\theta - 10^\circ, \theta + 10^\circ]$, and $[\theta - 5^\circ, \theta + 5^\circ]$, respectively. Then the retrieved radial velocities are obtained using the retrieved winds according to Eq. (2). The simulated and retrieved radial velocities on a range circle are shown in Fig. 1.

The simulated radial velocities without alias (original velocities) are shown by the solid line in Fig. 1a, and the aliased velocities are shown by dotted line. The velocities around the azimuth angle 200° are aliased because the velocities are larger than the Nyquist velocity of 18 m s^{-1} . Some of the velocities are aliased around the azimuth angle 20° due to random noise, which makes the velocities here varying around the Nyquist velocity. We can see that the alias velocities cause disrupted changes of radar radial velocities. The V-IVAP method retrieves the velocities unaffected

TABLE 1. The parameters of the three radars.

Radar	Location	Gate spacing (m)	Azimuthal increment ($^\circ$)	Elevation angle ($^\circ$)	Nyquist velocity (m s^{-1})
Yanchen (YC)	33.43°N, 120.20°E	250	1	0.61, 1.54, 2.50, 3.43, 4.39, 5.93, 10.06, 14.72, 19.55	27.8
Liangyungang (LY)	34.65°N, 119.29°E	250	1	0.57, 1.32, 2.29, 3.21, 4.17, 5.88, 9.75, 14.41, 19.33	27.0
Huaian (HA)	33.24°N, 118.83°E	250	1	0.61, 1.32, 2.46, 3.29, 4.31, 5.97, 9.75, 14.59, 19.33	27.2

FIG. 6. (a) Raw and (b)–(d) dealiased radar radial velocities (shading) using (b) the V-IVAP method retrieved radial velocities (contours) with a retrieval sector of $2.5^\circ \times 2.5^\circ$ or the IVAP method with retrieval sectors of (c) $0.2^\circ \times 0.2^\circ$ and (d) $0.06^\circ \times 0.06^\circ$ from the Lianyungang (LY) radar using the tilt of elevation angle 3.21° at 0625 UTC 23 Jun 2016.

by the alias of velocities, as shown by the solid lines in Figs. 1b–e. However, because the V-IVAP method uses the azimuthal variance of radial velocities along the range circle, it is sensitive to the noise in radial velocities. When the size of the retrieval sector is large, it can smooth out the noise (Figs. 1b–d). When the size of the retrieval sector is small, the noise in radial velocity causes obvious errors (Figs. 1e,f). Therefore, the V-IVAP method is helpful to produce reference velocity using a larger size of retrieval sector. In other words, the V-IVAP method can be used to obtain large-scale reference velocities. It is also shown that, instead of averaged wind within the range circle retrieved by the modified VAD method, the V-IVAP method can retrieve locally averaged wind within in a given area instead of within a full circle. For example, in Fig. 1d the winds at every point (with azimuth angle θ) are retrieved using the observations within the sector of $[\theta - 20^\circ, \theta + 20^\circ]$. Generally, if there are more than two available observations, the V-IVAP method can retrieve the winds within the area. However, we should keep in mind that the fewer the observations used, the larger the errors induced by the noise.

The V-IVAP and modified VAD methods share the same advantage; that is, they are not sensitive to alias of velocity. However, the V-IVAP method has the advantage for small spatial scale of velocities. To implement the modified VAD, a large coverage of the available data within the circle of a range is required. In Gong et al. (2003), the range with more than 55% data coverage was used to retrieve the wind. The V-IVAP method can be used even when the data coverage is small, while larger coverage gives higher quality. Figure 2 is an example using the V-IVAP method when the data coverage is relatively small. At 0431 UTC 23 June 2016, Yancheng radar observed only a part of the weather system. On the tilt of 5.93° , some of the velocities in the west were aliased (red in Fig. 2a). Using the V-IVAP method, the winds are retrieved within this area, and the aliased velocities are corrected according to the retrieved winds.

The V-IVAP method is helpful for correcting large-scale aliased velocities, but is not reliable for small-scale aliased velocities because its noise sensitivity. However, the IVAP method is helpful for filtering small-scale disrupted changes due to its high-frequency filtering property. This is shown by another example

FIG. 7. As in Fig. 6, but for (a) raw and (b) dealiased radar radial velocity (solid line) and retrieved velocity (dashed line) using the V-IVAP method for the cross section of range 111.25 km (range gate 445), which crosses the center of the tornado.

using the same simulated radial velocities in Fig. 1. The IVAP method of Eq. (3) is used to retrieve the wind with azimuth angle sectors of $[\theta - 90^\circ, \theta + 90^\circ]$, $[\theta - 45^\circ, \theta + 45^\circ]$, $[\theta - 20^\circ, \theta + 20^\circ]$, $[\theta - 10^\circ, \theta + 10^\circ]$, and $[\theta - 5^\circ, \theta + 5^\circ]$, respectively, which are the same as those in the V-IVAP example. The IVAP method is sensitive to aliased velocities, but it has the high-frequency filtering property. In Figs. 3b–f, the retrieved velocities are smooth except for some disrupted changes caused by aliased radial velocities. The disrupted changes are indicated by big differences between radar radial velocities and retrieved velocities (Figs. 3b–f), especially the disrupted changes caused by small-scale aliased velocities (such as the radar radial velocities within the azimuthal angles of 1° – 30°). Within the azimuth angles of 170° – 210° , the scale of aliased velocities is relatively larger. The retrieved velocities in this region with large retrieval sector are far apart from the aliased velocities (Figs. 3b,c), and are close to the aliased ones when the retrieval sector is small (Fig. 3f). It is shown that a bigger retrieval sector is helpful for indicating the disrupted changes caused by large-scale aliased velocities (Figs. 3b,c) and a smaller one is helpful for small-scale aliased

velocities (Figs. 3e,f). Instead of gate-to-gate continuity checking used in most of the research and applications (Eilts and Smith 1990; Jing and Wiener 1993; Yamada and Chong 1999; James and Houze 2001; Tabary et al. 2001; Gong et al. 2003; Gao et al. 2004; Haase and Landelius 2004; Zhang and Wang 2006; Zhu and Gong 2006; Xu et al. 2010, 2011), the IVAP method provides a way for regional continuity checking within a given area. The regional continuity checking is based on the high-frequency filtering function of the IVAP, and is accomplished by using the IVAP with varying retrieval sectors to correct large-scale to small-scale aliased velocities gradually.

Based on the alias insensitive property of the V-IVAP and small-scale noise filtering property of the IVAP, a two-step dealiasing procedure is developed. In the first step, the V-IVAP method is used to provide reference velocities for correcting large-scale aliased velocities. After the first step, there would be some small-scale aliased velocities. In the second step, the IVAP method is applied to indicate the small-scale aliased velocities. The size of the retrieval sector of the V-IVAP is usually a large one, and that of the IVAP varies from large to small for correcting relatively large-scale to small-scale aliased

FIG. 8. As in Fig. 6, but for zoomed in on the area shown by the box in Fig. 6.

velocities gradually. Therefore, the two-step aliasing procedure uses multiscale loops. Detail of the two-step aliasing procedure will be shown by using real cases next.

4. The framework of two-step dealiasing procedure and case study

a. Framework of two-step dealiasing procedure

The primary framework of the two-step dealiasing procedure based on V-IVAP and IVAP is shown in Fig. 4. The V-IVAP and IVAP methods are implemented in the longitude–latitude coordinate system to retrieve horizontal winds. The radar velocity data are projected in a longitude–latitude coordinate system.

In the first step of reference check, the V-IVAP method [Eq. (7)] is used to retrieve the winds with a large-size retrieval sector Ω . If the number of the observations within the sector is small (in this study, the threshold is set to 100) or the retrieved wind speed is larger than 60 m s^{-1} , the retrieved winds within this sector are invalid. The retrieved radial velocity is interpolated from the longitude–latitude to radar coordinate system to obtain the reference radar velocity. Then the radial velocity at each gate is compared to the reference velocity. If the difference is larger than the

Nyquist velocity, the radar velocity is adjusted using Eq. (1). The folding number n is determined according to Hennington (1981) and Gong et al. (2003) using

$$n = \text{integ}[(V_r^{\text{ref}} - V_r)/(2 \times V_r^N)], \quad (9)$$

where V_r^{ref} is the reference velocity, and $\text{integ}[\cdot]$ represents the nearest integer of $[\cdot]$. After the volume of the scans is checked, the corrected radial velocities are put at the start of the first reference check step again until there is not much points with large difference within the whole volume or the total number of the points with large difference is no decrease compare to previous cycle. Generally, three cycles are needed in the first step of reference checking.

After the reference check in the first step, the large-scale aliased velocities are corrected. The IVAP method is then used in the second step for reference check with a varying retrieval sector Ω from bigger to smaller one. In this step, there are a few cycles with difference sector size, and in each cycle, there are a few subcycles with the same sector size. For a given size of Ω , the IVAP method is used to retrieve the wind; then retrieved radial velocities were interpolated. As in the first step, the difference between retrieved velocity and radar velocity is compared at each gate and

FIG. 9. As in Fig. 7, but for the data along line A–B in Fig. 8.

corrected while the difference is large (bigger than the Nyquist speed). After the volume of the scans is checked, the radial velocities (with the corrected data) are put at the start of the second step with the same sector size. Newly retrieved winds are calculated again, and the difference between retrieved velocity and radar velocity is checked again. This cycle will be ended when there are not many points with a large difference within the whole volume or the total number of the points with a large difference is not decreased compared to the previous cycle, and then a new size of the sector Ω is set. A new cycle will start with a new size of sector Ω . The second step will end when cycles are finished for all given sizes of Ω .

b. Data

A tornado ranked EF4 occurred on 23 June 2016 at the Funing County of Jiangsu Province, China, which caused 98 fatalities and 846 injuries in the county (Xue et al. 2016; Zheng et al. 2016; Meng et al. 2018). This tornado was captured by three radars in Yanchen (YC), Liangyungang (LY), and Huaian (HA). The locations of the tornado and the radars are shown in Fig. 5. The raw data are from these three radars from 0608 to 0654 UTC with a time interval of 6 min. The

times of the scans of the three radars were not synchronized, and there were a few minutes of difference, which is not taken into account in this study. The parameters of the radar observations are listed in Table 1.

To demonstrate the reliability of the two-step dealiasing procedure, the data of the radar network of the Chinese Meteorological Administration are also used. There are 143 available radars at 0800 UTC 23 June.

The data were preprocessed by the quality-control procedures of gross error checking (velocity larger than Nyquist speed is omitted), isolated point (the point whose surrounding points are without valid value) removing and ground clutter removing. The near-zero velocities (less than 1.0 m s^{-1}) were also removed.

c. Test of the two-step dealiasing procedure

In this experiment, the radial velocities are projected in a longitude–latitude coordinate system with a horizontal resolution of $0.005^\circ \times 0.005^\circ$, a vertical resolution of 500 m, and 30 levels. The retrieval sector in the first step is set to a size of $2.5^\circ \times 2.5^\circ$ (500×500 grid points). The retrieved radial velocities are used as references. The radar radial velocities are compared with the references at every radar gate. Figures 6a,b and 7 are examples of the first step. The raw radial velocities

FIG. 10. As in Fig. 6, but for the Yancheng radar.

of LY radar on the tilt with elevation angle of 3.21° at 0625 UTC are shown as shading in Fig. 6a. There are large-scale aliased velocities within the azimuth angles of 10° – 80° and 190° – 220° (counterclockwise direction from the east) and the ranges of 50–100 and 100–150 km, respectively. The raw velocities along the range 111.25 km (range gate 445) are shown as a solid line in Fig. 7a. The retrieved radial velocities are shown as contours in Fig. 6b and as dashed lines in Fig. 7a. Even with large-scale aliased velocities, the V-IVAP method is able to retrieve the radial velocities close to the actual values. The aliased velocities are corrected according to the difference between radar radial velocity and retrieved radial velocity. The dealiasing radial velocities are shown as shading in Fig. 6b and as a solid line in Fig. 7b. The retrieved radial velocities using the dealiasing velocities are shown as contours in Fig. 6b and as dashed lines in Figs. 7a and 7b. We can see that the V-IVAP method provides excellent references for dealiasing.

In the second step, IVAP method is used to retrieve the reference velocity. In this study, the size of Ω is changed from $0.2^\circ \times 0.2^\circ$ to $0.06^\circ \times 0.06^\circ$. The dealiasing and retrieved velocities are shown in Figs. 6c and 6d, respectively. In Fig. 6c, within the rectangle labeled

“A,” there are small-scale aliased velocities (near azimuth angle 290° and range gate 445) related to the winds of the tornado. Detail of the small area of the rectangle in Fig. 6 is shown in Fig. 8.

When using the IVAP method with smaller retrieval sector of $0.2^\circ \times 0.2^\circ$, there are still some aliased velocities (shading in Fig. 8c and solid line in Fig. 9a). When using the sector of $0.06^\circ \times 0.06^\circ$, the retrieved radial velocities are helpful for checking the continuity of the velocities in a smaller area. The dealiasing radial velocities are shown as shading in Fig. 8d and as solid line in Fig. 9b, and the retrieved radial velocities are closer to the actual values.

In Fig. 9b, we can see that there are still disrupted changes, and in Fig. 8d we can see that these disrupted changes are caused by the wind shear of tornadic vortex. The IVAP method can take into consideration of the information of surrounding points to retrieve a smoother wind field, which is helpful for continuity checking. For the gate-to-gate checking method, it is a challenge to correct the disrupted change caused by the wind shear (such as those in Fig. 9b).

The raw data and dealiasing velocities of YC and HA radars in the tilt of 3.21° are shown in Figs. 10 and 11 and in Figs. 12 and 13, respectively. We can see that the

FIG. 11. As in Fig. 8, but for the Yancheng radar.

two-step dealiasing procedure can successfully correct the aliased velocities at both large and small scales. The choice of the sizes of retrieval sector Ω is a problem for this procedure. We tried many possible values in this study, and obtained better choices in this experiment. Results of the experiments for this case indicate that a better size of retrieval sector Ω for the V-IVAP method is on the order of $10^2 \text{ km} \times 10^2 \text{ km}$, and the size for the IVAP method varies from $10^1 \text{ km} \times 10^1 \text{ km}$ to $10^0 \text{ km} \times 10^0 \text{ km}$. The results of dealiasing are insensitive to the small change of the retrieval sector (e.g., difference in one order).

d. Retrieved winds using dealiasing velocities

The wind field is retrieved using dealiasing radar velocities. The terminal velocity of rainwater is calculated using the equation in Sun and Crook (1997), and is removed from the radar velocities. The radar velocities of the three radars are projected in a longitude–latitude coordinate system with a horizontal resolution of $0.005^\circ \times 0.005^\circ$ and a vertical resolution of 500 m. The longitude–latitude velocities are retrieved using Eq. (3) without considering vertical motion w . The retrieval sector Ω is set to $0.055^\circ \times 0.055^\circ$. The retrieved winds at the level of 1500 m from 0608 to 0654 UTC 23 June are

shown in Fig. 14. The tornado formed at 0614 UTC and dissipated at 0700 UTC in Funing County (Meng et al. 2018). The retrieved winds show the vortex being embodied in the southwesterly flow at 1500 m.

This experiment only shows the multiscale dealiasing function of the IVAP-based method. Xu et al. (2013) improved their two-step dealiasing procedure for storm-scale velocity dealiasing by improving alias-robust VAD to allow more raw data passing the reference check, and by adding and upgrading the two-way, block-to-point, and three-directional continuity check procedures. Later on, Xu et al. (2014; Xu and Nai 2017) improved the alias-robust VAD method and proposed the mesocyclone-targeted dealiasing procedure to dealias the velocities for small-scale vortex (even for tornadic mesocyclones). There are some differences among the IVAP-based method, the alias-robust VAD method, and the point-to-point continuity checking method. Comparison between these methods is beyond the scope of this study, but will be carried out in the future.

The V-IVAP and IVAP methods can be applied on a rectangle or cube in a longitude–latitude coordinate, or in a radar coordinate. The advantage of using longitude–latitude coordinate, as done in this study, is that the

FIG. 12. As in Fig. 6, but for the Huaian radar.

winds can be retrieved in the longitude–latitude coordinate using all available radars simultaneously. In Eqs. (3) and (7), the parameters θ and ϕ are radar-location independent when the radars are all north pointing and vertical pointing. This is another advantage of multiradar retrieval by using the IVAP-based method compared to the VAD-based method. This is also the reason why we can retrieve the tornadic vortex by using radar data only (Fig. 14).

e. Test using radar network data

The radar network radial velocity data at 0800 UTC 23 June are dealiased using the two-step dealiasing procedure. An alias index is used to indicate the amount of the aliased velocity points. As we know that velocity alias generally causes disrupted velocity change between neighboring points. The alias index is defined as the total numbers of the points at which larger velocity differences (greater than 1.6 times the Nyquist speed in this study) with neighboring points exist along an azimuth or a radius. For the total 143 radars with 9 tilts, 360 azimuth angles, and 460 gates, the alias index is 33 851 (it means that there are 33 851 points that have disrupted velocity change from a neighboring point) in the raw data (Fig. 15). After the first

reference check cycle using V-IVAP with sector size of $2.5^\circ \times 2.5^\circ$, the alias index is reduced to 4128; the four cycles in the first step reduce the alias index to 3914. In the second step, five cycles using IVAP method with the retrieval sector of $0.4^\circ \times 0.4^\circ$ reduce the index to 984, three cycles with the sector of $0.2^\circ \times 0.2^\circ$ reduce the index to 742, and three cycles with the sector of $0.1^\circ \times 0.1^\circ$ to 565. In this experiment, the horizontal resolution of the longitude–latitude coordinate is 0.05° because a bigger domain is adopted. No further reduction of the alias index can be reached when using a smaller sector size in this experiment (the minimum size is $0.05^\circ \times 0.05^\circ$ in this experiment, limited by the resolution of the longitude–latitude coordinate). There might be some disrupted velocity changes induced by random errors. Compared to the total number of the initial alias index (33 851) of the raw data, the final alias index (565) is rather small.

In Fig. 15 we can see that the reference checking using V-IVAP method with retrieval sector of $2.5^\circ \times 2.5^\circ$ (of order $10^2 \text{ km} \times 10^2 \text{ km}$) corrected most of the dealiased velocities. Changing the size of the sector from $0.4^\circ \times 0.4^\circ$ to $0.2^\circ \times 0.2^\circ$ (of order $10^1 \text{ km} \times 10^1 \text{ km}$) only changed the alias index from 954 to 742.

FIG. 13. As in Fig. 8, but for the Huaian radar.

It means that a small change of the sector size does not make a big difference. In the last experiment (Figs. 8, 11, and 13), we can see that if we focus on the small-scale weather system, a finer retrieval sector with order of $10^0 \text{ km} \times 10^0 \text{ km}$ is helpful.

The two experiments (three radars for tornadic vortex and 143 radars for large-scale wind field) indicate that the size of retrieval sectors can be choose as $10^2 \text{ km} \times 10^2 \text{ km}$ for V-IVAP reference checking and $10^1 \text{ km} \times 10^1 \text{ km}$ and $10^0 \text{ km} \times 10^0 \text{ km}$ for IVAP in this IVAP-based two-step dealiasing procedure.

Besides the small alias index for the dealiased velocities, the retrieved winds are also used to show the reliability of the two-step dealiasing procedure. The retrieval sector is set to $0.25^\circ \times 0.25^\circ$ for obtaining a relatively smooth wind field (Fig. 16). We can see that the retrieved winds by using radars only show the cyclone and the jet obviously.

5. Conclusions and discussion

In this study, an improved version of the IVAP method using azimuthal variance of radial velocity is proposed, namely, the V-IVAP method. This method is insensitive to aliasing of radar radial velocities. Though

the V-IVAP method is insensitive to aliasing, it is sensitive to the noise of radial velocity because of its differential form. Therefore, this method can be used to calculate large-scale reference velocity for velocity dealiasing. The most importance advantage of the V-IVAP method is that it can retrieve local winds instead of the full circle average winds if the modified VAD method is used.

For the two-step dealiasing procedure developed in this study, the first reference check step is based on the V-IVAP method. In this step, the large-scale aliased velocities are corrected. The second reference check step is accomplished by the multiscale (varying retrieval sectors from large to small ones) IVAP method. In this step, the aliased velocities are corrected gradually from large to small scales.

The reference check step using the V-IVAP method is based on locally retrieved winds instead of full circle averaged winds by the modified VAD method. The result is more accurate. Furthermore, the V-IVAP method does not require full (or almost full) coverage of the data within a range circle. The reference check using the IVAP method provides a regional continuity checking instead of gate-by-gate checking, and it can check the regional continuity from a large area

FIG. 14. Retrieved winds from (a) 0608 to (i) 0654 UTC 23 Jun 2016 at the vertical level of 1500 m. Shading is reflectivity, and the blue line is the track of the tornado.

to a small area gradually to correct the large- to small-scale alias.

The performance of the automatic dealiasing procedure is demonstrated by retrieving wind fields of an actual tornado. The retrieved winds show a clear mesoscale vortex compared to the aliased radar velocities. A test based on radar network data with the results of an alias index and retrieved wind fields is also carried out. The idealized and real-case experiments confirm this two-step dealiasing procedure is reliable.

Because the cycles of winds retrieving are processed gate to gate with varying retrieval sectors, much more computing resources are required for the proposed two-step dealiasing procedure. However, there are ways to reduce the computing requirement, such as by adopting initial-guess reference winds from a numerical model and by retrieving winds only around the points where velocities are changed disrupt. The capability of retrieving winds using all available radars simultaneously gives this

new method the potential to save computing resources of dealiasing for a radar network. In this paper, we only focus on the possibility for using the IVAP-based methods in velocity dealiasing. More studies will be carried out in future, including detailed comparison between IVAP-based method, VAD-based method, and gate-to-gate continuity checking method.

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FIG. 15. Changes of the alias index (ordinate) of the radar network data with cycles of difference retrieval sectors (abscissa) during the two-step dealiasing procedure.

FIG. 16. The retrieved wind fields at (a) 1500, (b) 3000, and (c) 5000 m with a retrieval sector of $0.25^\circ \times 0.25^\circ$. The locations of radars are indicated by letter R.

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