J5A.1 A NOVEL DE–ALIASING ALGORITHM FOR RADAR RADIAL WIND VELOCITIES

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1. INTRODUCTION

A Doppler radar uses electromagnetic waves to investigate atmospheric properties: the amplitude of the waves is used to estimate the reflectivity and the phase is used to estimate the radial wind.

The radial velocity of scattering particles is determined from their observed phase difference between successive radar pulses. There is a maximum velocity that can be determined unambiguously. This maximum velocity is called the Nyquist velocity

$$V_a = \frac{\mathsf{PRF}\ \lambda}{4}\ , \qquad (1)$$

where PRF is the *pulse repetition frequency* of the radar pulses and λ is the wavelength of the radar (e.g. 5 cm for C-band radars). The time between two successive radar pulses, and thus the PRF, also determines the maximum range that can be resolved unambiguously. This leads to the fundamental equation for the maximum Nyquist range and radial velocity measurable by a Doppler radar:

$$R_a\ V_a = \frac{c\ \lambda}{8}\ , \qquad (2)$$

where c is the speed of light. Therefore, a trade-off has to be made between the maximum velocity and the maximum range. For a typical C-band radar with a maximum range of 250 km, a maximum velocity of only 7.875 m/s is obtained. Velocities higher than the unambiguous velocity will be folded back into the fundamental velocity interval. This process is called "aliasing". The observed radial velocity (V_o) is therefore related to the true velocity through

$$V = V_o + 2nV_a\ , \qquad (3)$$

where n is an unknown integer called the Nyquist number.

There exist two main approaches to tackling the aliasing problem: one is based on improving the measurement technique of the radar system, like staggering PRFs (e.g. *Sachidananda and Zrnić*, 2000), and one focuses on post-processing methods (e.g. *Wüest et al.*, 2000).

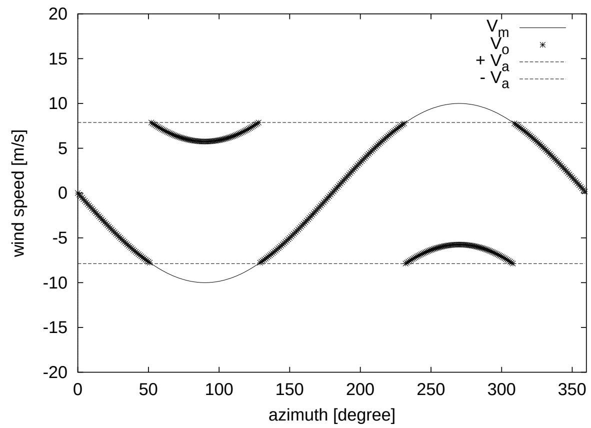
This abstract presents and briefly discusses a novel de-aliasing algorithm for Doppler radar velocity data, which has been developed recently at SMHI.

2. METHOD

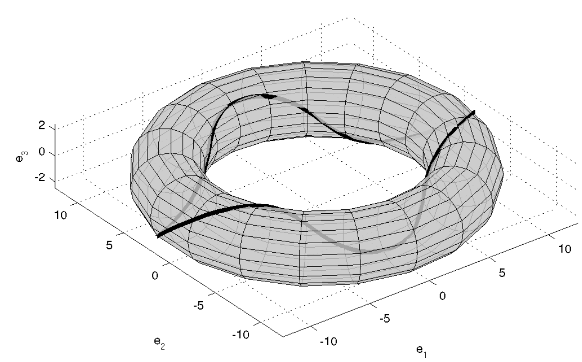
The new method is based on a linear wind model (V_m), in which the radial wind speed in a specified height interval can be expressed as a function of azimuth (Φ) and elevation angle (Θ):

$$V_m(u, v) = (-u \sin\Phi + v \cos\Phi) \cos\Theta\ . \qquad (4)$$

It should be mentioned that the zonal (u) and meridional wind speeds (v) are assumed to be proportional to the horizontal transport of precipitation. For the sake of simplification, the vertical velocity of hydrometeors is neglected. Assuming that the elevation angle and the distance to the radar are constant, each observation at a given azimuth angle is assigned a radial velocity. Unfortunately, the resulting curve could have discontinuities due to aliasing difficulties (Fig. 1a). To avoid this problem, we



(a) Classic projection onto a plane.



(b) Mapping onto the surface of a torus.

Figure 1: Two different projections of a homogeneous wind field observed by a Doppler radar (V_a = 7.875 m/s).

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map the measurements onto the surface of a torus and yield a continuous parametric curve (Fig. 1b):

$$\begin{aligned} F(\Phi) &= \underbrace{\cos\Phi\left[R+\frac{V_a}{\pi}\sin\left(V_m\frac{\pi}{V_a}\right)\right]}_{F_1}\vec{e}_1 + \\ &\quad \underbrace{\sin\Phi\left[R+\frac{V_a}{\pi}\cos\left(V_m\frac{\pi}{V_a}\right)\right]}_{F_2}\vec{e}_2 + \\ &\quad \underbrace{\frac{V_a}{\pi}\cos\left(V_m\frac{\pi}{V_a}\right)}_{F_3}\vec{e}_3\,. \end{aligned} \quad (5)$$

The unit vectors $\vec{e}_1$, $\vec{e}_2$ and $\vec{e}_3$ describe the geometry of the new system. The choice of the torus radius R is arbitrary as long as $R>\frac{V_a}{\pi}$. In the next stage, the third component of the tangent vector along all azimuth angles is calculated:

$$\begin{aligned} \frac{\partial F_3}{\partial \Phi} &= -\frac{\partial V_m}{\partial \Phi}\sin\left(V_m\frac{\pi}{V_a}\right) \\ &= u\,\cos\Phi\cos\Theta\sin\left(V_m\frac{\pi}{V_a}\right) + \\ &\quad v\,\sin\Phi\cos\Theta\sin\left(V_m\frac{\pi}{V_a}\right). \end{aligned} \quad (6)$$

Because $V_m \approx V = V_o + 2nV_a$ and

$$\sin\left(V_m\frac{\pi}{V_a}\right) \approx \sin\left(V_o\frac{\pi}{V_a}+2n\pi\right) = \sin\left(V_o\frac{\pi}{V_a}\right)$$

(6) can be transformed to

$$\begin{aligned} \underbrace{\frac{\partial F_3}{\partial \Phi}}_{D} &\approx u\,\underbrace{\cos\Phi\cos\Theta\sin\left(V_o\frac{\pi}{V_a}\right)}_{a} + \\ &\quad v\,\underbrace{\sin\Phi\cos\Theta\sin\left(V_o\frac{\pi}{V_a}\right)}_{b}. \end{aligned} \quad (7)$$

Using N estimates of D, a and b from an area where the model assumption (4) is reasonable, it is possible to solve for the model velocities u and v using least squares:

$$\begin{pmatrix}\tilde{u}\\ \tilde{v}\end{pmatrix} = \min_{u,v}\left|D_k - (u\,a_k + v\,b_k)\right|^2,\ k=1,...,N. \quad (8)$$

Finally, the wind speeds $\tilde{u}$ and $\tilde{v}$ are inserted in (4) and used to de-alias the observed radial wind velocities:

$$n = \min_i\left|V_o + 2iV_a - \tilde{V}_m\right|,\ i=\{-2,-1,0,1,2\}. \quad (9)$$

The real radial velocity is obtained by inserting n in (3).

3. DISCUSSION

3.1 Example

In order to verify the quality of the new de-aliasing technique, we ran numerous experiments with aliased synthetic data. The results reveal a perfect reconstruction of the prescribed wind fields (not shown).

Additionally, we generated wind profiles based on the VVP (volume velocity processing) method (*Waldteufel and Corbin*, 1979). Typically, the VVP technique is applied to thin layers of data at successive heights to obtain a wind profile. Wind speed and direction can be extracted via a multi-dimensional and multi-parameter linear fit of all observations in a certain height layer. For a case study, we used single-PRF data from the Finnish radar network, because they are more affected by aliasing than Swedish data.

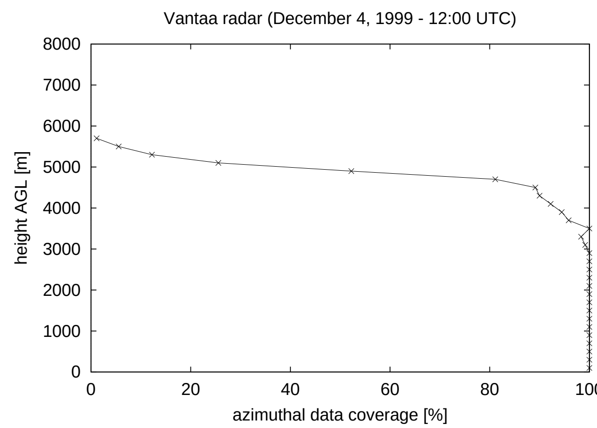


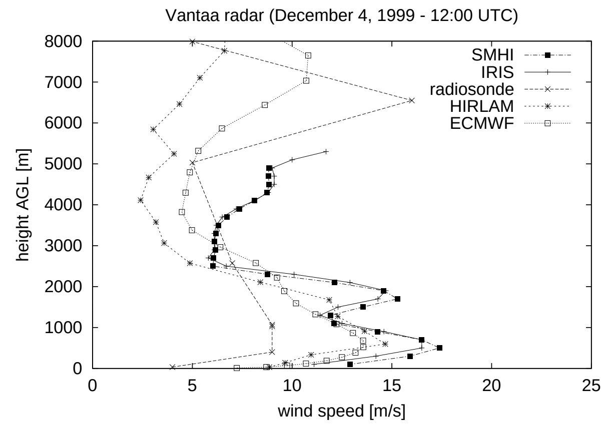
Figure 2: Azimuthal radar data coverage versus height for Vantaa radar (60.27°N, 24.87°E) on December 4, 1999 at 12 UTC.

Figure 2 shows the azimuthal radar data coverage versus height for the Vantaa radar on December 4, 1999 at 12 UTC. Between ground level and 2900 m height, measurements from all directions are used in the VVP technique. Above 2900 m, the number of unique azimuth angles decreases drastically which results in a more erroneous wind retrieval at these altitudes. This should be considered when interpreting the wind profiles. If the azimuthal data coverage is less than 33.3% the wind retrieval is rejected at this height level.

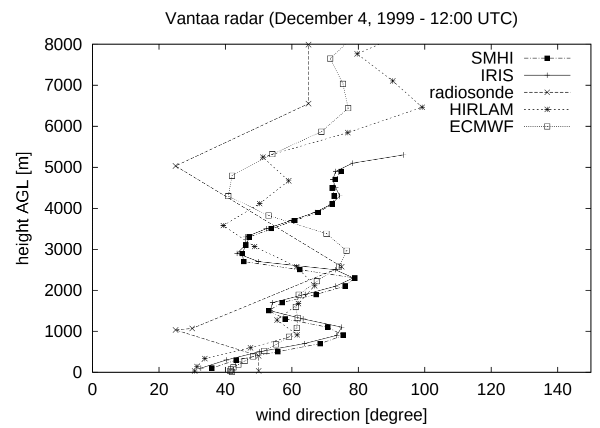
3.2 Evaluation

A comparison of vertical profiles of wind speed and direction generated by commercial radar software (SIGMET's IRIS$^{\mathrm{TM}}$ package) and our new algorithm (SMHI) is presented in Fig. 3 (same date and radar location as in Fig. 2). Note that both techniques use the same (aliased) radar radial wind observations as input. It is clearly visible that the two curves almost coincide. Long-term comparisons (30 hours) between both de-aliasing algorithms for five Finnish radars reveal mostly good agreement. Discrepancies can be explained by the different VVP algorithms. When the IRIS system is implemented at SMHI this year, we will apply its VVP technique to generate wind profiles using SMHI's de-aliased data sets as well.

Unfortunately, there is no radiosonde sounding available for the radar location in Vantaa (Finland). Instead, the radiosonde observation for Tallin (Estonia) is shown



(a) Vertical profiles of wind speed.



(b) Vertical profiles of wind direction.

Figure 3: Vertical profiles of wind speed and direction generated by IRIS and our new algorithm (SMHI) using the same radar radial wind data (date and radar location are the same as in Fig. 2). Additionally, wind profiles from a six hour HIRLAM forecast, an ECMWF analysis, and a radiosonde sounding for Tallin (59.38°N, 24.58°E) are shown.

in Fig. 3 (approximately 100 km distance from Vantaa). Although the vertical resolution is much lower than for the radar measurements, structures in the wind speed and direction fields are similar. The HIRLAM (High Resolution Limited Area Model; *Undén et al.*, 2002) forecast (22 km grid point spacing, no assimilation of radar winds) and the ECMWF analysis reveal the same trend as the radar observations, however not as detailed. Therefore, forecasts would probably benefit from an assimilation of de-aliased radar radial winds (Sec. 3.3).

3.3 Next steps

Since commercial algorithms provide only one- or two-dimensional wind products, we will use our new method to correct polar volumes as well. These can be applied to variational assimilation schemes through the generation of so-called super-observations. A super-observation is an intelligently generalized observation created through smoothing in space, based on high resolution data. It includes also a number of derived variables which collectively serve to describe the characteristics of a given observation. At SMHI, a method for generation of radial wind super-observations through horizontal averaging in polar space of the raw polar volume data is already implemented (*Lindskog et al.*, 2002). The radial wind super-observations have been used for the development of a Doppler data assimilation system for HIRLAM. Their use is expected to improve with the introduction of the proposed de-aliasing method.

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