Upper Air Wind Measurements by Weather Radar

Iwan Holleman, Henk Benschop, and Jitze van der Meulen
Royal Netherlands Meteorological Institute
e-mail: `holleman@knmi.nl`

Abstract

Doppler weather radars can be employed to determine wind profiles at a high temporal resolution. Several algorithms and quality ensuring procedures for the extraction of wind profiles from radar volume data have been published. A comparison and verification of the extracted wind profiles has been performed at KNMI. The observation minus background statistics of the weather radar wind profiles against the Hirlam NWP model are at least as good as those of the radiosonde profiles. This result clearly demonstrates the high quality of weather radar wind profiles.

1 Introduction

Weather radars are well known for their ability to detect precipitation at a high spatial and temporal resolution. Precipitation data deduced from reflectivity measurements by weather radars are extensively used for monitoring of (severe) weather and are increasingly used for hydrological applications. The majority of the operational weather radars in Europe is capable of performing Doppler measurements. Using the Doppler technique, the environmental wind can be extracted from the motion of the precipitation. The wavelength of weather radars is optimized for detection of precipitation and is typically 5 or 10 cm. In clear air, therefore, no return signal and thus no wind information is expected, but often (weak) signal is received from the boundary layer, moisture gradients, or large cloud particles. KNMI operates two C-band Doppler weather radars from Gematronik GmbH which are amongst others used for obtaining wind profiles.

A Doppler radar only measures the component of the velocity vector in the line of sight, the so-called radial velocity. Radial velocity data is not straightforward to interpret, some further processing is required before it can be presented to users or assimilated into numerical weather prediction (NWP) models. Under the assumption of a linear wind field within the analyzed volume, profiles of the wind speed and direction, vertical velocity, and divergence can be extracted from radial velocity data. Several algorithms for the extraction of wind profiles have been developed, most notably Velocity Azimuth Display (VAD) (Lhermitte and Atlas, 1961; Browning and Wexler, 1968) and Volume Velocity Processing (VVP) (Waldteufel and Corbin, 1979).

Here we present an extensive verification of VVP wind profiles against radiosonde and Hirlam model profiles. Nine months of wind profile data have been used for this verification. Different implementations of modules to retrieve wind profiles from Doppler volume scan data

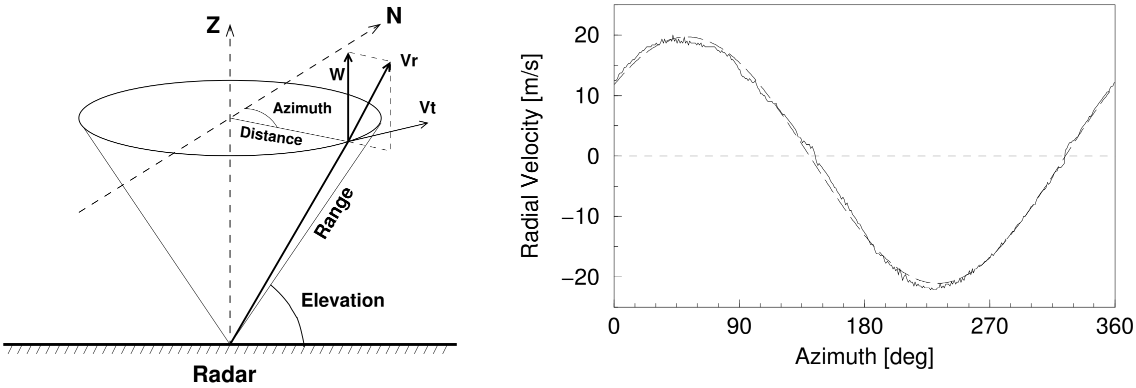

Figure 1: Schematic overview of the radar geometry used to measure Doppler wind profiles is given in left part of the figure. An example of a VAD extracted from radial velocity data is shown together with a fitted sine on the right.

using the VAD and VVP techniques have been considered as well. It is found that the most simple implementation of the VVP technique, i.e., with the fewest wind field parameters, provides the best horizontal wind data. The verification results indicate that the biases of the VVP wind profiles satisfy the accuracy requirements for upper-air wind measurements as provided by WMO (1996). The observation minus background statistics of the VVP wind profiles against the Hirlam NWP model demonstrate the high quality of weather radar wind profiles.

2 Wind Profile Retrieval: VAD and VVP

A Doppler weather radar measures the radial component of the velocity of scattering hydrometeors. The Doppler weather radar performs a three-dimensional scan and thus provides the mean radial velocity as a function of range, azimuth, and elevation. In the case of single-Doppler radar wind profile retrieval, information on the local wind field has to be deduced from these radial velocity volume data only. A schematic overview of the typical Doppler radar geometry and the relevant local wind field vectors is presented in figure 1. The figure shows clearly the three scanning directions of a (Doppler) weather radar and the three components of the local wind field: the radial velocity V_r, the tangential velocity V_t, and the vertical velocity w. Because only one of these components V_r can be observed by the Doppler radar, the other two components of the wind field have to be estimated using a local wind model.

Wind profiles can be obtained from single-site radial velocity data under the assumption of a linear wind model. In this model, the wind field in the vicinity of the radar is approximated by:

$$U(x,y,z) = u_0 + x\frac{\partial u}{\partial x} + y\frac{\partial u}{\partial y} + (z-z_0)\frac{\partial u}{\partial z} \tag{1}$$

$$V(x,y,z) = v_0 + x\frac{\partial v}{\partial x} + y\frac{\partial v}{\partial y} + (z-z_0)\frac{\partial v}{\partial z} \tag{2}$$

$$W(x, y, z) \quad = \quad w_0 + (z - z_0)\frac{\partial w}{\partial z} \tag{3}$$

The derivatives of the vertical velocity W in x- and y-directions can be neglected with respect to the derivatives of U and V in z-direction (Waldteufel and Corbin, 1979). In addition to the movement due to the wind, the hydrometeors have a fall velocity ($W_f < 0$). Using a uniform wind field and a constant fall velocity, the radial velocity V_r can be calculated as a function of azimuth (ϕ) and elevation (θ):

$$V_r \quad = \quad (w_0 + W_f)\sin\theta + u_0\cos\theta\sin\phi + v_0\cos\theta\cos\phi \tag{4}$$

When Doppler radar data is displayed at constant range and elevation, the radial velocity as a function of azimuth will have the form of a sine, see figure 1. The wind speed and direction can be determined from the amplitude and the phase of the sine, respectively. This technique is called Velocity-Azimuth Display (VAD) (Lhermitte and Atlas, 1961; Browning and Wexler, 1968).

Instead of processing multiple VADs and averaging the results, one can also process all available velocity volume data within a certain height layer at once. The parameters of the linear wind field can then be extracted using a multi-dimensional and multi-parameter linear fit. This so-called Volume Velocity Processing technique (VVP) has been introduced by Waldteufel and Corbin (1979). It has been a matter of debate whether or not the VVP method for retrieval of wind profiles is as robust as the VAD method, because the VVP basis functions are not inherently orthogonal. It has already been mentioned, however, that the orthogonality of the VAD basis functions is reduced by the presence of gaps in the collected data (Matejka and Srivastava, 1991). Boccippio (1995) presents a robust and stable implementation of the VVP method.

3 Error sources and Quality Control

The retrieval methods for wind profiles approximate the local wind field by a uniform or a linear wind model. Inevitably deviations of the local wind field from the wind model will cause errors in the retrieved wind parameters. Caya and Zawadzki (1992) have investigated the effect of nonlinearity of the local wind field on the quality of the VAD retrieval. Errors due to nonlinearities of the wind field are controlled by application of a maximum range (e.g. 25 km) on the analyzed volume data.

Sidelobe clutter and other ground clutter in the received Doppler signal is suppressed using a digital time domain filter before the mean radial velocity is calculated. Strong clutter is not suppressed completely, however, and it will cause a bias of the mean radial velocity towards zero. Application of a minimum range (e.g. 5 km) on the analyzed volume data and rejection of data from low elevations reduces the impact of clutter on the quality of the wind profiles. In addition, the error can effectively be controlled by rejection of all radial velocities close to zero before the wind profile retrieval method is applied.

The absence of hydrometeors or other scatterers leads to gaps in the radial velocity data. Wind profile retrieval algorithms have problems with large gaps, because the basis functions loose orthogonality and the linear fit becomes unstable. To avoid gross errors, no wind field retrieval should be performed on volume data with large gaps.

The unambiguous interval of the radial velocity data is extended by a factor of 3 using the dual-PRF technique (Sirmans et al., 1976). Analysis of dual-PRF velocity data has revealed that a small fraction of the range bins will be dealiased incorrectly (Holleman and Beekhuis, 2003). These velocity outliers constitute typically 1 percent of the range bins, and the velocity error will be twice the unambiguous velocity of the primary observations. The velocity outliers can efficiently be flagged by a comparison with the modeled radial velocity obtained from a first fit. After removal of the outliers the final wind field parameters are again determined by a second wind model fit.

Migrating birds and actively flying insects are a major source of error for wind profile retrieval methods (Koistinen, 2000; Collins, 2001). Bird migration can easily be recognized by inconsistency of the wind vectors or by deviation of the Doppler wind profiles from reference profiles. Koistinen (2000) has noted that the standard deviation of the radial velocity determined from the wind profile retrieval is larger in bird migration than in rain. The retrieved wind vectors are quality controlled by rejection of the vectors with a standard deviation larger than a certain threshold.

4 Verification of Radar Wind Profiles

The intercomparison of different implementations of the VAD and VVP wind profile retrieval methods using radiosonde profiles as a reference revealed that the VVP method performs slightly better than the VAD method (Holleman, 2003). Furthermore it was found that the most simple implementation of the VVP retrieval method, i.e., using a uniform wind field, provides the best horizontal wind data. Figure 2 shows a timeseries of weather radar (VVP) and Hirlam NWP wind profiles for 8 January 2005 between 06 and 12 UTC in black and blue, respectively. On this day a low pressure area with strong winds moved over the Netherlands. In figure 2 wind speeds up to 50 m/s are observed between 4 and 6 km altitude. Evidently the agreement between the radar and model wind vectors is good, but the update frequency and availability are different.

Histograms of the wind speeds observed by Doppler radar have been constructed for three different height ranges. The constructed histograms for the 0-2 km, 2-4 km, and 4-6 km height ranges are shown in figure 3. The vertical axis represents the wind vector count per 1 m/s-wide bin using all available radar wind profiles between 1 October 2001 and 30 June 2002. Comparing the histograms for the three height ranges, it is evident that the total number of available wind vectors and the mean wind speed are decreasing and increasing, respectively, with increasing height. The fraction of the number of available wind vectors to the maximum number of vectors decreases from 0.39 at ground level to 0.16 at 6 km altitude.

The observation minus background statistics for the weather radar (upper frames) and ra-

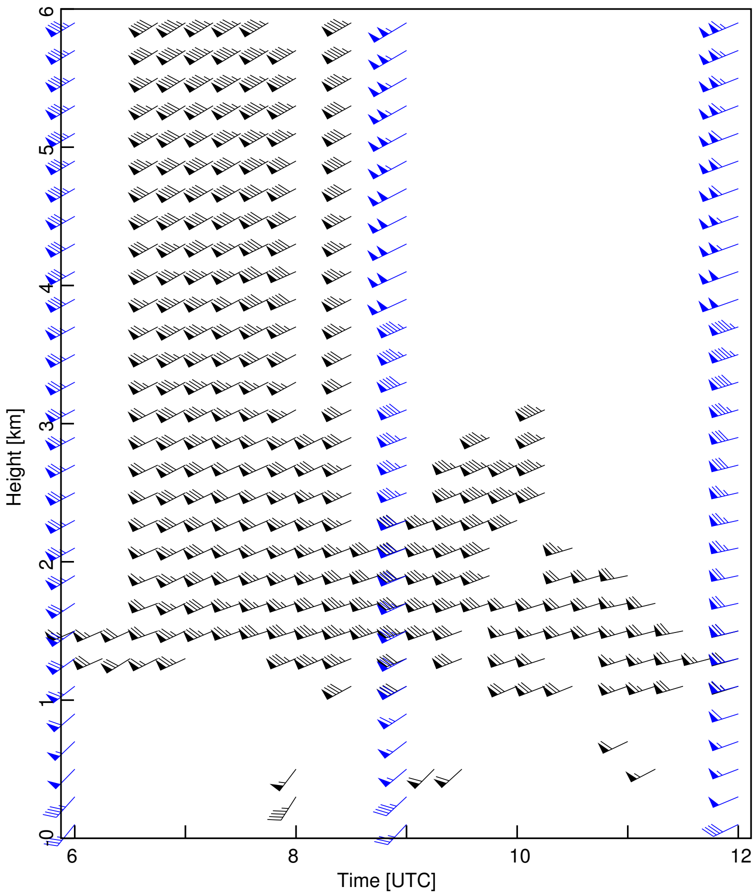

Figure 2: A time-height plot with the weather radar wind vectors (VVP) for 8 January 2005 between 06 and 12 UTC. The wind profiles from the Hirlam NWP model are overlayed in blue. Wind speed and direction are indicated by wind vanes. Each full barb represents a wind speed of 5 m/s and each triangle a wind speed of 25 m/s.

diosonde (lower frames) wind profiles against the Hirlam NWP model are shown in figure 4. The figure shows the bias and standard deviation of the Cartesian u- and v-components of the wind vectors calculated for the 9 months verification period (1 October 2001 and 30 June 2002). In this comparison the radiosonde has a clear advantage over the weather radar because the radiosonde profiles are assimilated by the Hirlam model. It is therefore not a surprise that the observed biases of the wind vector components from the radiosonde are only a few tenths m s^{-1} and thus negligible. The standard deviation of the radiosonde wind vector components against the Hirlam background is between 1.5 and 2.0 m s^{-1} at ground level and gradually increases to almost 3.0 m s^{-1} aloft. This increase is probably due to the increase of the wind speeds with height and to the drifting of the radiosonde. For the radar wind data, a small positive bias for both Cartesian components is found. The standard deviation of the VVP wind vector components against the Hirlam background is around 2.0 m s^{-1} at ground level and about

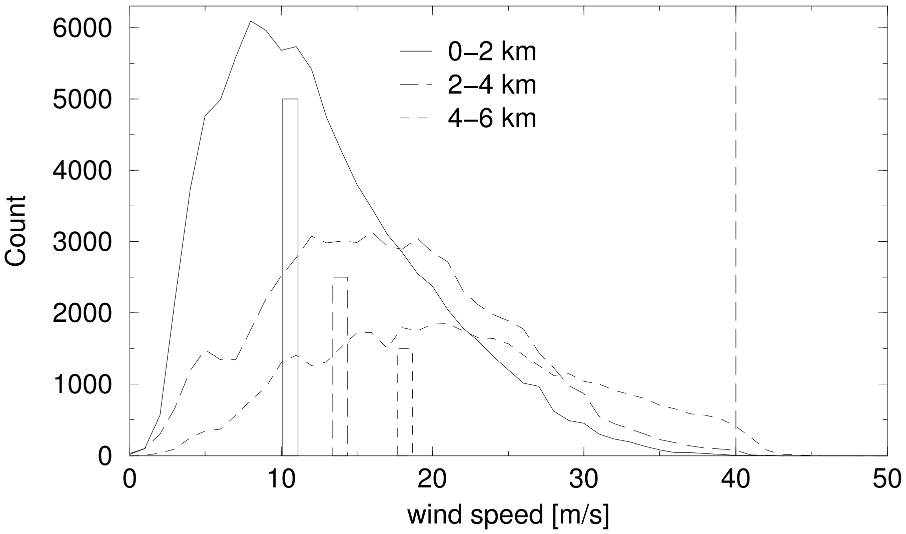

Figure 3: This figure shows histograms of the observed wind speeds for three different height layers and using wind speed bins of 1 m/s. The wind speeds are obtained from the radar using the VVP retrieval method. The vertical bars represent the mean wind speeds as obtained from the radiosonde observations over the same period.

2.5 m s^{-1} aloft. Figure 4 shows that observation minus background statistics of the weather radar wind profiles are at least as good as those of the radiosonde profiles. This result evidently demonstrates the high quality of the weather radar wind profiles.

5 Conclusions

In many meteorological circumstances, a Doppler weather radar can provide wind profiles at a high temporal resolution. It was found that the most simple implementation of the VVP retrieval method provides the best horizontal wind data. An availability fraction of weather radar wind vectors of about 0.39 is found in the lowest 1 km of the troposphere, and this availability drops below 0.16 at 6 km altitude.

A comparison of the observation minus background statistics for the radar and radiosonde wind profiles against the Hirlam NWP model has been performed. The observed biases of the wind vector components are negligible for the radiosonde data and slightly positive for the radar data. The observed standard deviation of the radiosonde and radar wind vector components is comparable at ground level and it is slightly lower for the radar data at higher altitudes. Thus the observation minus background statistics of the weather radar wind profiles are at least as good as those of the radiosonde profiles. This result demonstrates the high quality of (quality controlled) weather radar wind profiles.

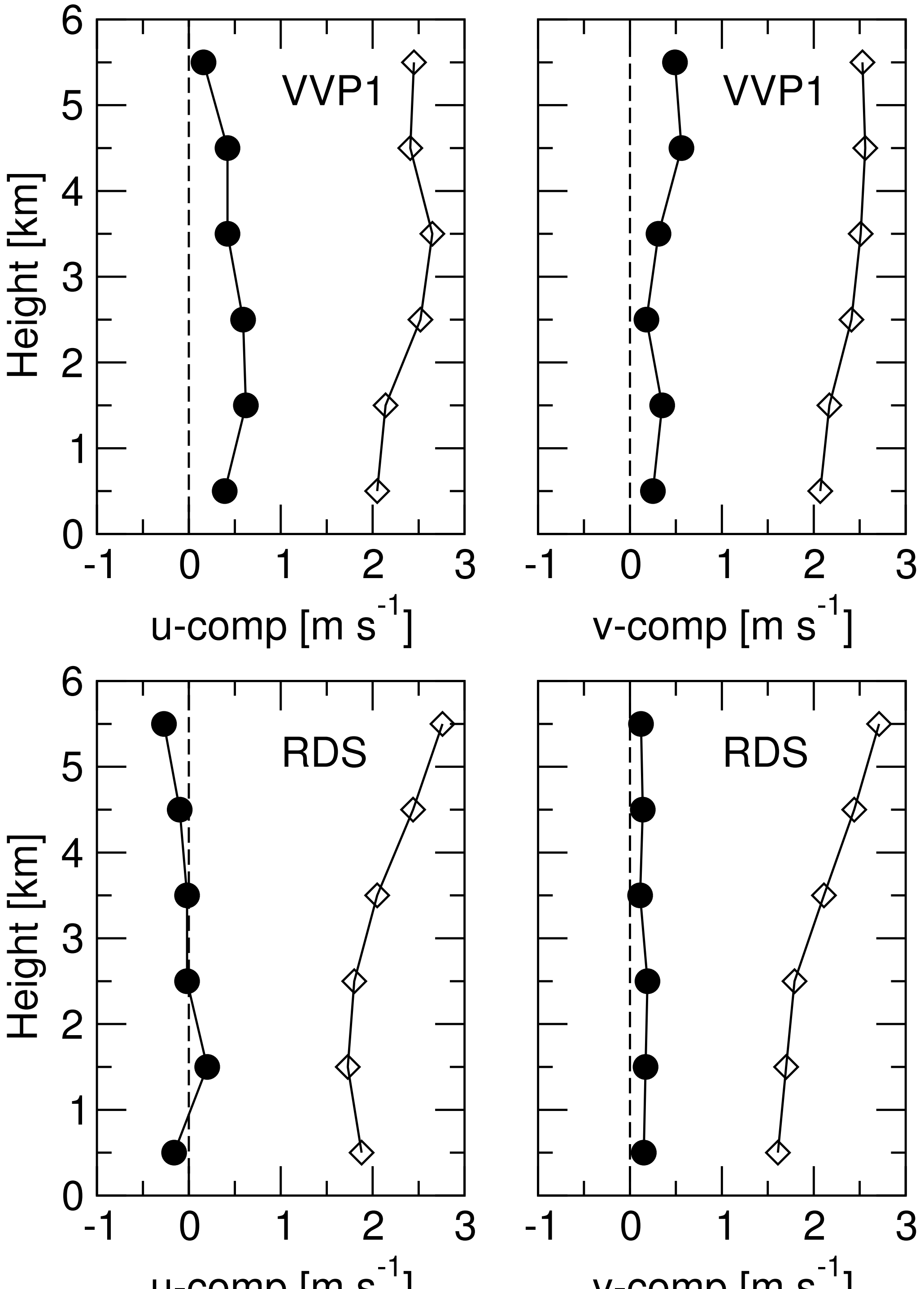

Figure 4: Profiles of the bias (•) and standard deviation (◇) of the Cartesian u- and v-components from the verification of the radar (upper) and radiosonde (lower) wind data against the Hirlam model.

Acknowledgments

Hans Beekhuis and Sylvia Barlag are gratefully acknowledged for their feedback and support. This work is done in the framework of the EU COST-717 action "Use of Weather Radar Observations in Hydrological and NWP models".

References

Boccippio, D. J.: 1995, A Diagnostic Analysis of the VVP Single-Doppler Retrieval Technique. *J. Atmos. Ocean. Technol.*, **12**, 230–248.

Browning, K. A. and R. Wexler: 1968, The determination of kinematic properties of a wind field using Doppler radar. *J. Appl. Meteor.*, **7**, 105–113.

Caya, D. and I. Zawadzki: 1992, VAD Analysis of Nonlinear Wind Fields. *J. Atmos. Ocean. Technol.*, **9**, 575–587.

Collins, W. G.: 2001, The Quality Control of Velocity Azimuth Display (VAD) Winds at the National Centers for Environmental Prediction. *11th Symposium on Meteorological Observations and Instrumentation*, AMS, 317–320.

Holleman, I.: 2003, Doppler Radar Wind Profiles. Scientific report WR-2003-02, Royal Netherlands Meteorological Institute (KNMI).

Holleman, I. and H. Beekhuis: 2003, Analysis and Correction of Dual-PRF Velocity Data. *J. Atmos. Ocean. Technol.*, **20**, 443–453.

Koistinen, J.: 2000, Bird migration patterns on weather radars. *Phys. Chem. Earth (B)*, **25**, 1185–1194.

Lhermitte, R. M. and D. Atlas: 1961, Precipitation motion by pulse Doppler radar. *9th conference on Radar Meteorology*, AMS, 218–223.

Matejka, T. and R. C. Srivastava: 1991, An Improved Version of the Extended Velocity-Azimuth Display Analysis of Single-Doppler Radar Data. *J. Atmos. Ocean. Technol.*, **8**, 453–466.

Sirmans, D., D. Zrnić, and B. Bumgarner: 1976, Extension of Maximum Unambiguous Doppler Velocity by Use of Two Sampling Rates. *17th conference on Radar Meteorology*, Seattle, WA, AMS, 23–28.

Waldteufel, P. and H. Corbin: 1979, On the analysis of single Doppler radar data. *J. Appl. Meteor.*, **18**, 532–542.

WMO: 1996, *Guide to Meteorological Instruments and Methods of Observation, No. 8.* Secretariat WMO, Geneva, Switzerland, sixth edition.