Wind profiles generated with a scanning cloud radar

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1 Introduction

Since summer 2005 IMK operates the novel cloud radar MIRA36-S. One special feature of this 35.5 GHz radar is its scanning capability, which allows antenna motion between 0° and 360° in azimuth and between -45° and +45° relative to the local zenith.

One benefit of this feature is the possibility to derive profiles of the wind vector from PPI scans. From the algorithmic point of view the procedure is identical to that for precipitation radars. However, some differences between cloud and precipitation radars require some further investigations to get the best results:

- Due to a missing dual PRF ability the cloud radar’s maximum unambiguous velocity \( V_{\text{unamb}} \) is smaller (typically 10.5 m/s) than it can be achieved for precipitation radar, leading to more severe folding problems.

- The contribution of the vertical velocity to the radial velocity is larger compared to precipitation radars because of the larger elevation angles used.

- Thus, inhomogeneities in the fall velocities might introduce errors in the derived horizontal wind data.

The free parameter of a PPI scan is the zenith angle. A larger zenith angle (smaller elevation angle) leads to (i) a larger contribution of the horizontal wind to the radial component and (ii) a larger region from which the measurements stem such that the vertical movement of scatterers may contribute differently in different volumes. Accordingly, the question arises if an optimal zenith angle can be determined providing best velocity data.

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<table>
<thead>
<tr>
<th>Radar type</th>
<th>Monostatic, pulsed, magnetron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>35.5 GHz ± 0.2 GHz</td>
</tr>
<tr>
<td>Peak power</td>
<td>30 kW</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>max 1:500; typically 1:1000</td>
</tr>
<tr>
<td>Pulse width</td>
<td>100, 200, and 400 ns</td>
</tr>
<tr>
<td>Minimum range</td>
<td>150 m</td>
</tr>
<tr>
<td>Maximum range</td>
<td>15 km (500 range gates)</td>
</tr>
<tr>
<td>Doppler velocity resolution</td>
<td>0.02 m/s</td>
</tr>
<tr>
<td>Pulse repetition frequency (PRF)</td>
<td>2.5 kHz, 5kHz, and 10 kHz</td>
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<tr>
<td>FFT length</td>
<td>128, 256, 512, 1024</td>
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<tr>
<td>Minimum averaging time</td>
<td>0.1 s</td>
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<tr>
<td>Antenna type</td>
<td>Cassegrain</td>
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<tr>
<td>Diameter of antenna</td>
<td>1.2 m</td>
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<tr>
<td>Antenna beam width (6 dB/two-way)</td>
<td>0.52° x 0.52°</td>
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<tr>
<td>Antenna gain</td>
<td>50.4 dBi</td>
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<tr>
<td>Polarisation isolation</td>
<td>-35 dB</td>
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<tr>
<td>Precision for antenna positioning</td>
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<tr>
<td>Scan range</td>
<td>-183°...+183°</td>
</tr>
<tr>
<td>Azimuth angles</td>
<td>-45°...+45°</td>
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<tr>
<td>Zenith angles</td>
<td>3.4 dB (LNA)</td>
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<tr>
<td>Receiver noise figure (LNA + following)</td>
<td>2.3 dB (T-R-switch), 0.4 dB (waveguides receiving path), 0.9 dB (w.g. + circ. transmitting path)</td>
</tr>
<tr>
<td>Sensitivity at 5 km, 5 kHz, 200 ns, NFFT=256, 0.1 s</td>
<td>-44 dBZ</td>
</tr>
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</table>

Table 1. Technical data of the MIRA36-S cloud radar.

2 Measurements

This presentation bases on measurements performed in November and December 2005 at the Meteorologisches Observatorium Lindenberg of the German Meteorological Service (DWD), about 50 km southeast of Berlin. To answer the question mentioned a certain scan strategy has been performed every 15 min: 4 PPI scans at 15°, 25°, 35°, and 45°, respectively, were done, each with an angular velocity of 6°/s and a resolution of 1 s and 30 m. Each PPI scan lasts 1 min. For further technical data see Tab. 1.
Fig. 1. Example of a single VAD analysis. Data from 5.12.2005, 1:47 local time. For description see section algorithm.

For comparison purposes 30 min. averages of the wind velocity, routinely measured by a 1290 MHz wind profiler from DWD up to 2000 m a.g.l. with a pulse width of 700 ns ($\Delta r = 100$ m) and vertical spacing of 500 ns (74 m) (Engelbart et al., 1996). The wind profiler was located roughly 500 m apart from the cloud radar.

### 3 Algorithm

The algorithm to derive the wind vector applied here bases on an improved version of the well known VAD algorithm (Browning and Wexler, 1968), which matches the measured $V_r(\theta)$ by

$$V_r \approx a_0 + a_1 \cos \theta + b_1 \sin \theta,$$

leading to $a_1 = u_0 \cos \varphi$ and $b_1 = u_0 \cos \varphi$, where $\varphi$ is the elevation angle. Neglecting divergence and convergence the parameter $a_0 = (u_0 - v_T) \sin \varphi$ gives the vertical component of the velocity of the scatterers, which differs from the wind velocity by the terminal fall velocity $v_T$. This algorithm fails in case of folded data.

With the aim to unfold velocity data Tabary et al. (2001) proposed to use the derivative of the radial velocity $V_r$ with respect to azimuth angle $\theta$ to determine the horizontal wind. I.e. not $V_r$ is itself fitted by a Fourier series but

$$\frac{dV_r}{d\theta} \approx -a_1 \sin \theta + b_1 \cos \theta,$$

which analytically leads to the same coefficients $a_1$ and $b_1$.

Fig. 1 shows in the upper panel a VAD of the radial velocity, measured by MIRA36-S at a zenith angle of 45°. A direct Fourier analysis does not provide reasonable wind data in this case.

In the middle panel of the figure the circles, connected by the dashed line, represent the derivative of the radial velocity. At the locations where the “folding jumps” appear (roughly 40°, 125°, 210°, and 315°), the derivative attains misleading high values. The values at these angles have to be excluded from the calculations.

The criterion for exclusion from analysis works as follows: The largest (theoretically) possible value for $|dV_r/d\theta|$ is $2V_{\text{unamb}}/\delta \theta$, where $\delta \theta$ is the azimuthal resolution of the data. Thus, we have to introduce a limit for $|dV_r/d\theta|$ being small compared to $2V_{\text{unamb}}/\delta \theta$.

On the other hand, the maximum of $|dV_r/d\theta|$ is identical to the maximum of $|V_r| = V_h \cos \varphi$, where $V_h$ is the horizontal wind speed. Avoiding to exclude too many data from the calculation demands that $dV_r/d\theta$ should be allowed to be larger than $V_{\text{unamb}}$.

In practice we found that the optimum limit is

$$\left| \frac{dV_r}{d\theta} \right|_{\text{lim}} = 2V_{\text{unamb}}.$$

It should be stressed that this criterion does not limit the maximum evaluatable velocity to only double the normal unambiguous velocity. At higher wind speeds the criterion only removes some data points where the derivative of the radial velocity is significantly large (in most cases this means that the radial velocity itself is comparable small at these angles). However, there are normally still enough data points left to determine appropriate Fourier coefficients $a_1$ and $b_1$.

Note, that the results depend on the azimuthal resolution $\delta \theta$. From

$$V_{\text{unamb}} < \left| \frac{dV_r}{d\theta} \right|_{\text{lim}} \ll 2V_{\text{unamb}}/\delta \theta$$
we find $\delta \theta \ll 2(\text{rad}) \approx 115^\circ$, i.e. $\delta \theta$ should be in the order of $10^\circ$ or less.

Fitting the not excluded values leads to the solid line in the middle panel of Fig. 1, with $a_1 = 14.9$ m/s and $b_1 = 1.9$ m/s.

So far, we followed the ideas of Tabary et al. (2001). On one hand, the differentiation helps to increase the maximum evaluable horizontal wind speed. On the other hand, differentiation of measured values increases the noise due to measurement uncertainties. Thus, the wind measurements that are derived directly from $dV_r/d\theta$ show an increased uncertainty compared to the classical VAD algorithm.

This disadvantage can be avoided by reanalysing the undifferentiated radial velocities. As an additional step of the algorithm the results from the analyses of the derivatives are used as a first guess of the horizontal wind velocity. The measured radial velocities (given by the crosses in the lower panel of Fig. 1) are compared with the expected radial velocities of the first guess (given by the solid line in the lower panel). The measured velocities are corrected by the appropriate multiple of $2V_{\text{ran},b}$, wherever measured and expected radial velocities differ more than $V_{\text{ran},b}$, leading to the unfolded values represented by the circles in the lower panel of Fig. 1. Thus, the first guess helps to unfold the measured radial velocities, which can now be used to apply a standard VAD algorithm.

Now a second Fourier analysis is performed, resulting in $a_2 = 15.5$ m/s and $b_2 = 2.0$ m/s.

A further benefit of this second step is that vertical velocity is recovered: The mean of the radial velocities gives the parameter $a_0$ (here: $-0.6$ m/s).

In principle this second step could be iterated. However, it turned out that the results from the first iteration could not significantly be improved.

4 Results

To estimate the quality of the derived wind profiles of MIRA36-S they are compared to the measurements of a wind profiler. A certain disadvantage of these data is, that the wind profiler only measures up to 2 km a.g.l and with a temporal resolution of 30 min. Cloud radar measurements cover the total height of the troposphere (depending on cloud occurrence) and reach a temporal resolution of up to 1 min.

An example of profiles of the wind velocity measured by MIRA36-S at the different zenith angles (solid lines) as well as the corresponding profile of the wind profiler (dotted line, only up to 2 km) is shown in Fig. 2. Horizontal wind speed and direction correspond very well. The deviation in wind speed at roughly 300 m height is probably not stable for half an hour and thus not seen in the wind profiler data. The deviations in the vertical velocity in the lowest 1000 m may be caused by a sensitivity to different scatterers with different fall velocities.

There are roughly 600 measured profiles at each zenith angle with 23 levels each, given by the range gates of the profiler. From these data roughly 20% were evaluable (depending on height and zenith angle), the rest were measured when no clouds occured in the lowest 2 km or when the wind profiler could not determine wind data (bad signal noise ratio). Consequently, we have more than 2500 data points for each zenith angle for comparison purposes.

The scatter plots of the measured horizontal wind speed, wind direction and vertical wind speed are shown in Fig. 3, Fig. 4, and Fig. 5, respectively. Quantitative values for the correlation coefficient $\rho$ and the slope $a$ and the offset $b$ of a linear fit are given in Tab. 2.

The agreement with regard to the horizontal wind speed and the wind direction is as good as it can be expected. For-
mer comparisons of the wind profiler data with data from other measuring devices show comparable results. The correspondence of data is nearly independent of the measuring height. The correlation decreases systematically below 400 m only. This is most likely due to the spatial and temporal inhomogeneity of the wind field in these low heights.

Wind direction is the parameter with the best correspondence between the two instruments. The slope of the linear fit is very close to 1 (which is due to the nature of the investigated parameter and not a quality of the instruments) whereas the offset depends on the precision of determining the correct north direction when installing the cloud radar. Thus, these parameters are not presented here.

For the horizontal velocity components it is a good approximation to assume that the velocity of the scatterers is identical to the wind velocity. In contrast, the vertical velocity of the scatterers is the sum of the wind velocity and their sedimentation velocity. Due to the very different wavelengths (8.5 mm versus 23 cm) the two devices do not necessarily “see” the same objects. Nevertheless, the scatter plot shows that both instruments detect mostly very small vertical velocities, and only in a few cases downward motions faster than 2 m/s. These large vertical velocities are exclusively observed below the melting layer. At levels larger than 1 km a.g.l. the vertical motion is restricted to velocities of less than 1.5 m/s for both devices.

Correlation of the vertical velocity component is worse than for horizontal components. This is (i) due to the above mentioned different wavelength and (ii) caused by the reduced range in which vertical motions vary whereas the statistical errors are comparable to those for horizontal components. This is especially evident in heights above the melting layer where the range of vertical velocities is stronger limited than below the melting layer. Whereas the correlation coefficient for vertical velocities is above 0.9 in the lowest 1 km, it decreases to roughly 0.6 at 1.7 km height.

The main motivation for this investigation was to answer the question for the best zenith angle to be used for wind speed estimation purposes. Whereas the horizontal component figure out to be nearly independent of the zenith angle, the vertical component shows are clear dependency: decreasing the zenith angle, i.e. measuring at nearly vertical incidence, leads to increasing correspondence with the wind profiler.

5 Conclusions

Based on the described algorithm, data from scanning cloud radars can be used to determine profiles of the wind velocity on a very reliable basis. This has been demonstrated by comparing wind profile data obtained by instruments operating with independent measuring methods: a scanning cloud radar and a wind profiler. In particular, it turns out that the determination of horizontal wind speed is independent of the used zenith angle, whereas the vertical component — which is the sum of the vertical wind component and the fall velocity of the scatterers — is improved as the zenith angle decreases. Besides, these profiles may be used to align the radar for performing RHI scans in the prevailing wind direction or perpendicular to it.

References