Vector wind field determination by bistatic multiple-Doppler radar

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Abstract. At Oberpfaffenhofen a bistatic Doppler radar network to determine wind vector fields was installed consisting of the transmitting C-band radar POLDIRAD and 3 bistatic receivers. The separation of transmitter and receiver results in a dependency of most radar properties (e.g. resolution volume, Nyquist velocity) on the scattering angle between transmitter, scatterer and bistatic receiver. Therefore, location of the receiving antennas play a major role in the distribution of variances of the horizontal wind field and will be discussed herein. The standard deviation of the horizontal wind field considering only geometrical issues within the inner part of the bistatic network is about 1-2 m/s.

Other sources that influences the accuracy of the wind field are discussed as well.

Furthermore, a procedure transforming the measured wind fields into quality-proved real-time wind vector fields is presented on measured wind fields.

An outlook of the technical concept of the bistatic multiple-Doppler network is given, e.g. the use of antennas with different horizontal and vertical opening angles depending on the investigation topic.

1 Introduction

The knowledge of the real 3D wind field is of great importance for practical usage, e.g. now-casting, as well as for investigation topics, e.g. vertical and horizontal transport processes and the propagation of chemical properties. The bistatic multiple-Doppler radar network is an addition to the monostatic Doppler radar and can provide horizontal wind fields within an area of about 40 *km x* 40 *km* in real time. This network includes one transmitting Doppler radar and several non-transmitting, low-gain antennas at remote sites (Fig. 1, Fig. 2). Because there is only one source of illumination each wind component is measured simultaneously and is assembled to a wind field.

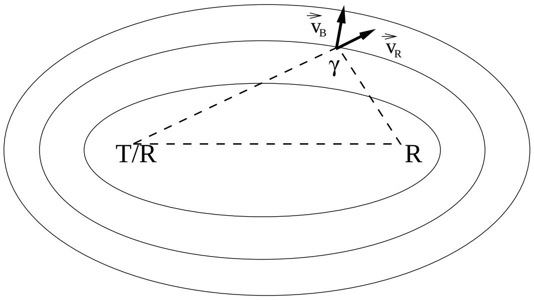

Fig. 1. Schematic view of the bistatic geometry with a monostatic Doppler radar (T/R) measuring the radial Doppler-velocity and a bistatic non-transmitting receiver (R) measuring the bistatic Doppler-velocity perpendicular to the ellipse of constant time delay. The scattering angle is represented by γ.

On one hand, the system is less sensitive to weak echos due to low-gain antennas with a horizontal opening angle of 60°. But on the other hand, the accuracy of the wind field determination can be improved by the geometrical arrangement of the low-cost bistatic receivers. In this study, the bistatic Doppler radar is introduced and differences to the monostatic Doppler radar are represented. Furthermore, the sources that influences the accuracy of the wind field determination are investigated. The procedure transforming the measured wind fields into quality proved real time wind vector fields is presented for measurements provided by the transmitting Doppler radar POLDIRAD and the bistatic receivers at DLR in Oberpfaffenhofen.

2 Comparison of monostatic and bistatic Doppler radar

An introduction to the concept of bistatic Doppler radar and a detailed description is given in Wurman et al.

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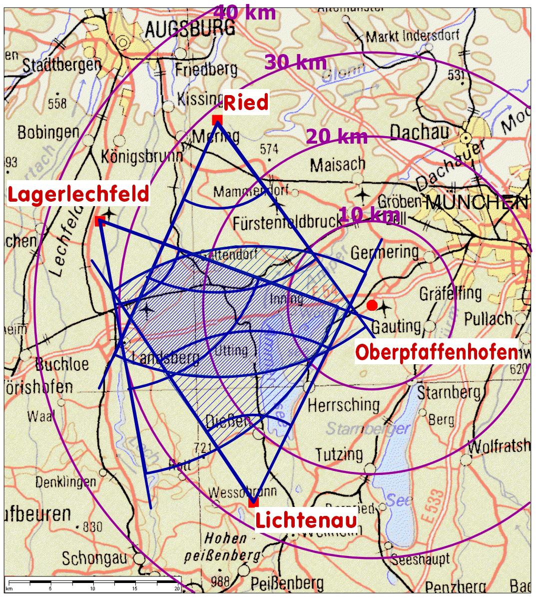


Fig. 2. Bistatic multiple-Doppler radar network at the DLR consisting of one transmitting polarization C-band Doppler radar (POLDIRAD) and three bistatic receivers. For each bistatic receiver the field of view (with a horizontal opening angle of 60°) is illustrated. Furthermore, areas in which the 3D and the horizontal wind field is determined or over-determined are hatched (intensity according to the number of illuminating receivers). Note, that the radial velocity can be measured by the monostatic Doppler radar for the total area illustrated with range rings every 10 km.

(1993) and in Protat and Zawadzki (1999).

Monostatic radar measurements are based on a polar coordinate system, while the bistatic measurements rest upon elliptic coordinates due to the separation of transmitter and receiver (Fig. 1). This leads to a difference in all properties that are related to changes in path length and can be expressed by the scattering angle γ (Fig. 1). Thus, for a bistatic Doppler radar the size and shape of the resolution volume as well as the Doppler- and Nyquist-velocity (for more detail see Protat and Zawadzki (1999)) vary with the scattering angle in contrast to the monostatic Doppler radar.

Beside range-dependency and receiver characteristics (as in the monostatic case), polarization of the electro-magnetic wave and the scattering angle influences the distribution of the minimum detectable signal at a remote site (Wurman et al., 1993).

Assuming Rayleigh scattering, the intensity I of the transmitted E vector received at the bistatic antenna changes as $I \sim I_0 \, sin^2 \gamma$ for horizontal polarization and $I \sim I_0 \, cos^2 \gamma$ vertical polarization (Doviak and Weil, 1972).

3 Accuracy of wind field determination

At a bistatic system the variance $\sigma^2_{v,bist}$ of the wind field is influenced by the geometry of receiver and transmitter (Fig. 1) and by the variance of the Doppler-velocity.

$$\sigma^2_{v,bist} = \sigma^2_{geom} + \sigma^2_{VR} \qquad (1)$$

The variance of the Doppler-velocity can be divided into sources induced by the receiver system, σ^2_{Rsys} and due to meteorological conditions, e.g. the vertical and horizontal wind shear and turbulence within the resolution volume σ^2_{WS}, the differential fall velocity of the hydrometeors σ^2_{FV} and the scanning rate of the antenna σ^2_{SA}.

$$\begin{aligned} \sigma^2_{VR} &= \sigma^2_{Rsys} + \sigma^2_{met} && (2) \\ \sigma^2_{met} &= \sigma^2_{WS} + \sigma^2_{FV} + \sigma^2_{SA} && (3) \end{aligned}$$

The variance induced by certain meteorological conditions σ^2_{met} can be treated similar to monostatic Doppler radar measurements.

Merely, the variance of the wind field influenced by difference of wind speed and direction within the resolution volume σ^2_{WS} occurs beside the horizontal and vertical direction also perpendicular to the ellipse. The whole variance induced by wind shear is the sum in each direction. High wind shear and turbulence is detected by high spectral width.

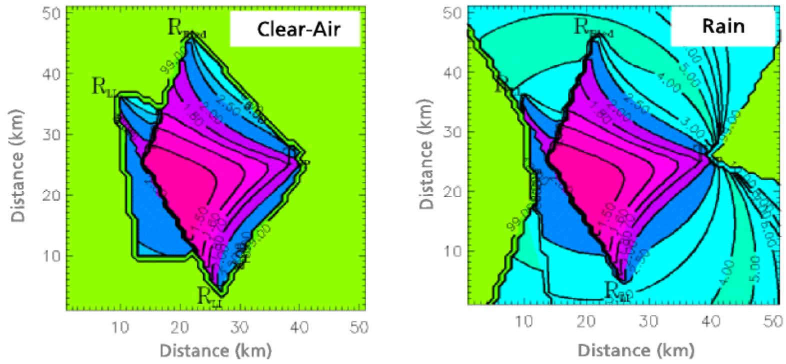
The geometrical induced variance σ^2_{geom} of the wind field depends primarily on the position of the scatterer (governed by the scattering angle, size of the resolution volume), the number of receivers (Wurman et al., 1993) as well as the field of view (Figs. 1, 2). All geometrical properties and the influence of the chosen polarization are summarized to σ^2_{geom} on behalf of the bistatic radar equation (Rogers and Eccles, 1971) and the decomposition of the bistatic wind component into u, v, w-components (Wurman et al., 1993).

The standard deviation of the horizontal wind field considering only the geometrical influence and vertical polarization, σ_{geom}, is about $1-2\,m/s$ ($\sigma_{v,mono} = 0.8\,m/s$) for the bistatic multiple-Doppler radar network (Fig. 3). For weak radar echos the wind field can only be retrieved within the region covered by all receivers (Figs. 1, 3a). At strong precipitation the individual receivers can be retrieve the Doppler-velocity at greater ranges (Fig. 3b). However, in this areas only one or two receivers can be used to retrieve the wind vector. This reduces the accuracy in contrast to the inner area, where all receivers contribute.

4 Procedure leading to quality proved wind vector fields

4.1 Quality improvement of the wind field

In the first step, two quality criteria are proposed to reduce the error evoked by geometrical distribution of the antenna. For this, only wind velocity measurements are considered within areas where the scattering angle



(a) (b)

Fig. 3. The distribution of the horizontal standard deviation σ_{geom} of a bistatic multiple-Doppler network as a multiple of the monostatic Doppler radar considering only geometrical issues (a) for rain ($Z \geq 40\ dBZ$) and (b) clear-air ($Z \geq 0\ dBZ$) at ground. The antenna gain of the receivers is 8 dB.

limit is between 25° and 140° and the Normalized Coherent Power (index related inversely to the spectral width ranging from 0 to 1) is at least 0.4 (Satoh and Wurman, 1999). If there are over-determined areas, the wind velocities of the different receivers are weighted according to the scattering angle and composited afterwards.

In the second step, the variance caused by turbulence is reduced by using a signal quality index (relationship between reflectivity and spectral width). Only wind vectors are taken into account with a Normalized Coherent Power above 0.4 as well as a certain reflectivity depending on the weather situation, e.g. rain: $Z \geq 10\ dBZ$, clear-air: $Z \geq -10\ dBZ$.

4.2 Unfolding procedure

Horizontal wind fields are determined by a dual Doppler-algorithm consisting of the radial component of the wind measured by the monostatic system and the bistatic component measured by the bistatic receiver (Fig. 1). The monostatic C-band Doppler-radar POLDIRAD operates with a PRF of 1200 Hz and results therefore, a Nyquist velocity of 16.35 m/s. A Monostatic wind field with a constant Nyquist-interval ($v_{N,mo}$) and a bistatic wind field with variable Nyquist-velocity [$v_{N,mo}/\ cos(\gamma/2)$] have to be unfolded separately and combined afterwards. An unfolding procedure for monostatic Doppler-velocity will be used (Curtis, 1999) for the monostatic velocity fields and will be transformed for a bistatic implementation.

4.3 Transformation into Cartesian coordinates

For further usage, e.g. data assimilation and implementation in mesoscale models, the velocity field has to be transformed from radar coordinates($R - \Theta$) into Cartesian coordinates (x,y,z). An interpolation schema is applied that uses the original data values from four neighbored beams (horizontally, vertically) surrounding each destination Cartesian location in space. Successive bilinear interpolation on each elevation plane and linear interpolation along elevation (using the estimates at these projection points in order to produce a resultant value at Cartesian location) is performed (Mohr et al., 1981).

After transforming the data into Cartesian coordinates the horizontal wind field is interpolated to a grid with a horizontal resolution of 1 km and the vertical resolution of 0.5 km.

4.4 3D wind field retrieval with variational analysis method

While the horizontal wind field can be measured directly from the measured Doppler-velocity, the vertical wind can not be retrieved directly, because of the low vertical opening angle of the bistatic receivers. Pointing the antenna vertically, only the vertical wind component can be measured and scatterer inducing high reflectivity are required when using vertical polarization.

Protat and Zawadzki (1999); Laroche and Zawadzki (1994) created a variational analyses method for 3D wind field retrieval that fulfills the continuity equation and is adjusted to the measured horizontal wind vectors. The vertical wind component is calculated on behalf of the equation of continuity and an upward/downward integration. Afterwards, the measured wind field is adjusted to a synthetic wind field over a cost function. This model is determined with just one bistatic receiver and is over-determined with additional ones.

5 Conclusion

A bistatic Doppler radar network is an appropriate tool to determine 3D wind fields within a limited area.

Several sites are necessary in order to get a quality proved 3D wind field. Firstly, erroneous Doppler-velocities have to be excluded ($NCP > 0.4$, $Z(rain) \geq 10\,dBZ$ or $Z(clear\text{-}air) \geq -10\ dBZ$). Secondly, the scattering angle has to be within $25° - 140°$ to allow the retrieval of the horizontal wind vectors (Satoh and Wurman, 1999). In overlapping areas the wind vectors are weighted by the scattering angle.

Although the bistatic Doppler-velocity has a high variance, it is possible to determine the horizontal wind field with an accuracy of about $1 - 2\ m/s$, when using several low-cost bistatic receivers.

The spatial resolution of the vector wind field is in the order of $150\ m - 450\ m$ for a $1\ \mu s$ radar pulse.

Facilitating the use of the wind field for further applications, the data are transformed into a Cartesian coordinate system.

Since only the horizontal wind field can be retrieved directly the vertical component can be estimated by a variational analysis method using the continuity equation (Protat and Zawadzki (1999); Laroche and Zawadzki (1994)).

Unfolding of the folded Doppler-velocity as well as the variational analysis method will be implemented.

Further up-grading of the DLR system is planned, e.g. antennas with different vertical opening angle for special investigation topics (for wind field measurements within thunderstorm 25°, within atmospheric boundary layer 8°).

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