Utilization of the coherency matrix in cloud radars

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1. Introduction

Nowadays polarization properties of electromagnetic waves are widely used in atmospheric remote sensing. During the last decades, a variety of polarimetric methods were developed for application in weather radars. These methods utilize the 3x3 covariance matrix to derive products such as differential reflectivity Z_{DR}, linear depolarization ratio (LDR), cross-channel correlation coefficient ρ_{hv}, and differential phase shift Φ_{hv}. The above-mentioned variables allow for a classification of meteorological targets and for a more accurate estimation of precipitation intensity in comparison to the methods based only on the measurement of the radar reflectivity.

Modern cloud radars, which operate in the Ka-band ($\sim$ 35 GHz) or W-band ($\sim$ 94 GHz), also have polarimetric capabilities. Many of them operate in the LDR-mode, when the horizontally polarized wave is emitted by the radar and both horizontal (co-polarized) and vertical (cross-polarized) components of the backscattered wave are received. Usually only the LDR is derived. In this mode also the 2x2 coherency matrix can be obtained that requires the availability of raw quadrature data (I/Q data). Even though some cloud radars allow saving quadrature components of the backscattered signals in the co- and cross-channels the raw data requires a huge amount of data space and is thus not saved routinely.

In this study we present an approach to conduct continuous measurements of the coherency matrix elements based on measurements performed with the cloud radar MIRA-35 of METEK GmbH and show their possible applications.

2. Measuring of the coherency matrix

It is known that the coherency matrix can be used for the statistical description of the electromagnetic waves. The coherency matrix can be written as follows:

$$\mathbf{J} = \begin{pmatrix} J_{11} & \dot{J}_{12} \\ \dot{J}_{21} & J_{22} \end{pmatrix}, \tag{2.1}$$

where

$$J_{11} = \langle \dot{E}_{co} \dot{E}^*_{co} \rangle \tag{2.2}$$

$$\dot{J}_{12} = \langle \dot{E}_{co} \dot{E}^*_{cr} \rangle \tag{2.3}$$

$$\dot{J}_{21} = \langle \dot{E}_{cr} \dot{E}^*_{co} \rangle \tag{2.4}$$

$$J_{22} = \langle \dot{E}_{cr} \dot{E}^*_{cr} \rangle. \tag{2.5}$$

$\dot{E}_{co}$ and $\dot{E}_{cr}$ are complex amplitudes of the received signals in the co- and cross-channel, respectively, $\langle\,\rangle$ means averaging over a number of pulses, $*$ is the complex conjugation sign. The complex amplitudes for every received pulse are expressed using the I and Q-components measured by the radar:

$$\dot{E}_x = I_x + iQ_x \tag{2.6}$$

$$\dot{E}_y = I_y + iQ_y \tag{2.7}$$

To calculate the coherency matrix automatically in continuous mode the default processing routine of the MIRA-35 radar was changed. The radar was switched to the mode when the I/Q data is saved to the standard pds-format. This data was then used for the calculation of the elements J_{11}, $\dot{J}_{12}$, and J_{22} of the coherency matrix. These elements were saved to a new special data format pdm. After processing the pds-file with I/Q data was removed.

Using J_{11}, $\dot{J}_{12}$, and J_{22} LDR and co-cross-channel correlation coefficient ρ can be obtained:

$$\text{LDR} = \frac{J_{22}}{J_{11}}. \tag{2.8}$$

$$\rho = \frac{|\dot{J}_{12}|}{\sqrt{J_{11} J_{22}}}. \tag{2.9}$$

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Physically, the value of ρ describes the width of the probability density function of the phase difference $\Delta\Phi$ between $\dot{E}_{co}$ and $\dot{E}_{cr}$. In Fig. 1 high value of ρ corresponds to a narrow distribution of the phase difference (e.g. $\rho = 1$ corresponds to the fully polarized wave), while $\rho = 0$ corresponds to uniform distribution (unpolarized wave).

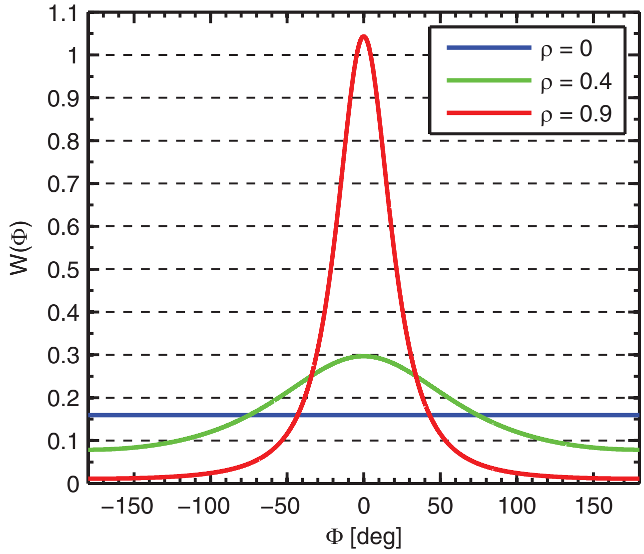

Figure 1: Centralized probability density function $W(\Phi)$, where $\Phi = \Delta\Phi - \langle\Delta\Phi\rangle$. Adopted from Kanareykin et al. (1966).

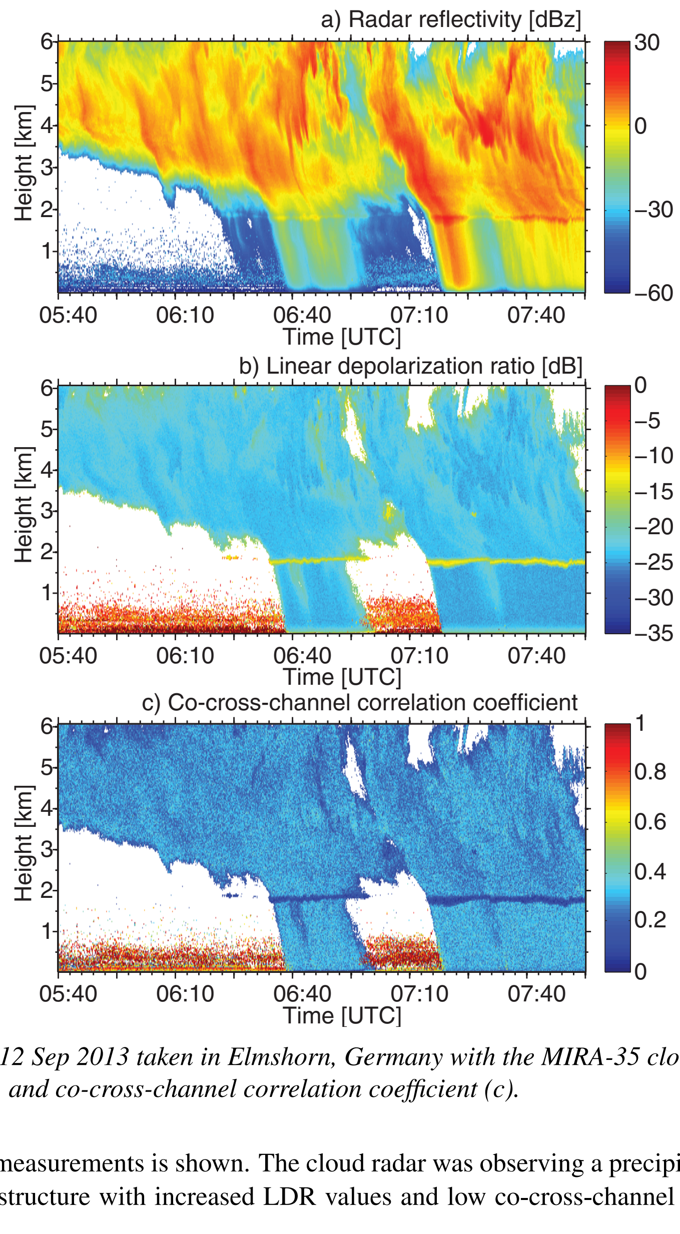

Figure 2: Measurements from 12 Sep 2013 taken in Elmshorn, Germany with the MIRA-35 cloud radar. Radar reflectivity (a), linear depolarization ratio (b), and co-cross-channel correlation coefficient (c).

In Fig. 2 an example of the measurements is shown. The cloud radar was observing a precipitating cloud system passing the METEK site. The horizontal structure with increased LDR values and low co-cross-channel correlation coefficient at about

1.7 km height corresponds to the melting layer. Below the melting layer light rain (the radar reflectivity does not exceed 30 dBz) was observed while above the melting layer falling ice was present. The values of ρ for these regions are in the range of 0.3–0.4. Regions with high LDR (> -10 dB) at heights below 700 m correspond to insects. It is noticeable, that insects are characterized by high values of ρ.

3. Applications of products of the coherency matrix

3.1. Separation of insects and hydrometeors

As it was shown before, low values of ρ correspond to the uniform distribution of the phase difference $\Delta\Phi$ (Fig. 1). In the melting layer such a distribution is formed due to the interfering behavior of the scattering of randomly oriented non-spherical particles. For insects ρ is high because insects can be considered as point targets producing strong depolarization. In this case there is much less interference (with respect to hydrometeors) occurring in the formation process of the backscattered wave. This leads to the narrow distribution of the phase difference $\Delta\Phi$ and thus to the high observed values of ρ (Fig. 1). The formation of ρ of 0.3–0.4 for regions with raindrops and falling ice crystals is considered in the next subsection. The differences in ρ for point and distributed targets provide an additional possibility for the separation of insects and hydrometeors (Myagkov et al., 2014). Especially this may be useful when insects occur very close to the melting layer.

3.2. Correction of the polarimetric measurements

Ideally, the cloud radar emits fully-polarized waves. Isotropic particles have the unit backscattering matrix and therefore do not change the polarization state of the wave. Therefore theoretical values of LDR and ρ for spherical raindrops are $-\infty$ (in the logarithmic scale) and 1, respectively. Nevertheless, in light rain the values of LDR and ρ observed by the MIRA-35 system (Fig. 2) were about -25 dB and 0.3–0.4, respectively. This can be explained by the polarization leakage from the co-channel to the cross-channel that is produced in the radar hardware and in particular by the radar antenna.

To characterize the polarization leakage, we carried out measurements of the complex antenna patterns. Our antenna measurements were based on the papers of Chandrasekar and Keeler (1993), and Mudukutore et al. (1995). The description of the measurements as well as the results are submitted to (Myagkov et al., 2014). The measurements have shown that the phase difference $\Delta\Phi$ between the signal in the co-channel and the leakage signal in the cross-channel is not constant over the antenna diagram, i.e., it depends on the elevation and azimuth angle of the received (and transmitted) wave. When isotropic targets are uniformly distributed in the radar beam the signal in the co-channel is the result of the interference of the signals scattered by every single particle. Therefore for every received pulse the direction of the wave incident at the radar antenna is fluctuating. This leads to the pulse-to-pulse change of the phase difference $\Delta\Phi$. In this case the received wave is partly-polarized.

We suppose a correction algorithm for LDR and ρ values based on the decomposition of the coherency matrix to the fully-polarized and non-polarized parts. We applied the correction to the measurement data from two collocated MIRA-35 radars with different qualities of the antennas. The comparison has shown a good agreement between the corrected LDR and ρ data of both radar systems. Only after the correction of LDR and ρ for polarization leakage, respective measurements of different radar systems are comparable. The details about the correction algorithm are submitted to (Myagkov et al., 2014).

3.3. Particles shape determination

It is shown by Matrosov et al. (2012) that measurements of scanning cloud radars operated in slanted LDR mode (SLDR) can be used to retrieve cloud particle shape. In Sep of 2013 the SLDR configuration was implemented by METEK company into a standard MIRA-35 cloud radar with a scanning unit. Over a period of several weeks the coherency matrix was measured as described in Sec. 2. Continuous elevations scans were performed in the range from 30 to 150 degrees with an angular velocity about 0.3 deg/sec. An example of such measurements is presented in Fig. 3. Range-height scans of SLDR and co-cross-channel correlation coefficient for a non-precipitating cloud system are shown. In Fig. 3a it can be seen that SLDR is independent of the elevation angle which indicates that the cloud particles have spherical shapes. At the same time the co-cross-channel correlation coefficient depends on the elevation angle. Please note, that uncorrected values of ρ are shown. The lowest values of ρ were observed in the case of vertical pointing of the radar antenna. The correspondent values are about 0.3 that is similar to the values of ρ observed by the same radar in light rain (Fig. 2). At lower elevation angles higher values of ρ were observed. Such increased values could indicate the presence of aligned slightly non-spherical ice particles inside the cloud. However, to derive the axis ratios of the cloud particles, a model is required that takes into account the influence of the radar hardware beside the scattering properties of the cloud particles.

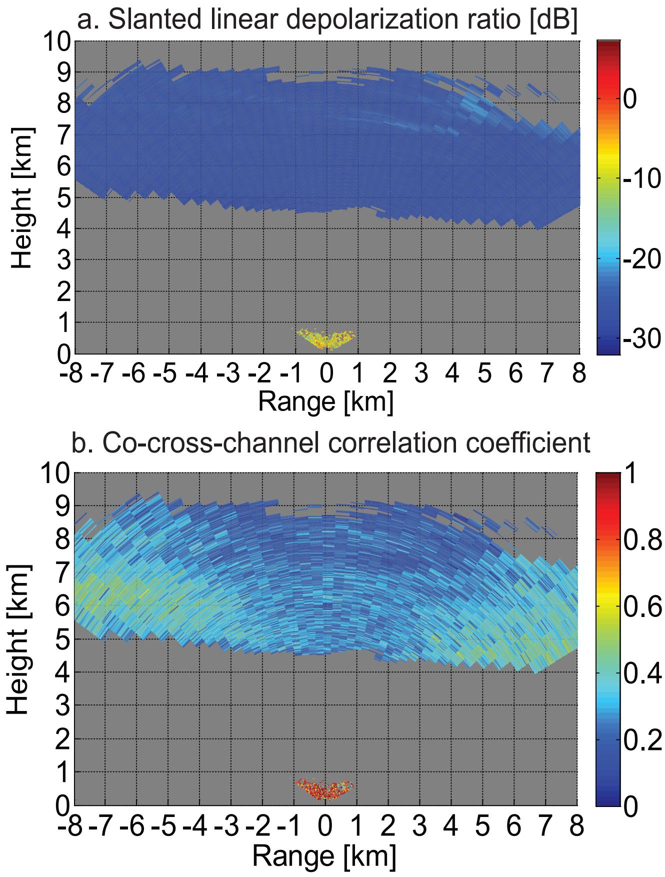

Figure 3: Measurements from 8 Sep 2013, Elmshorn, Germany. Slanted linear depolarization ratio (a) and co-cross-channel correlation coefficient (b) observed from 19:37–19:44.

4. Summary

Polarimetric techniques used in weather radars can be successfully applied to cloud radars. For example, the utilization of the coherency matrix in cloud radars provides additional possibilities for the classification of targets, improving the data quality, and development of algorithms for the retrieval of microphysical properties of cloud particles. To achieve these goals further investigations concerning all available polarimetric information and optimal scanning regimes are required and need to be applied to long-term measurements of the coherency matrix.

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