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Preliminary evaluation of polarimetric parameters from a new dual-polarization C-band weather radar in an alpine region

H. Paulitsch, F. Teschl, and W. L. Randeu

Department of Broadband Communications, Graz University of Technology, Austria

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Abstract. The first operational weather radar with dual polarization capabilities was recently installed in Austria. The use of polarimetric radar variables rises several expectations: an increased accuracy of the rain rate estimation compared to standard Z-R relationships, a reliable use of attenuation correction methods, and finally hydrometeor classification. In this study the polarimetric variables of precipitation events are investigated and the operational quality of the parameters is discussed. For the new weather radar also several polarimetric rain rate estimators, which are based on the horizontal polarization radar reflectivity, Z_{H}, the differential reflectivity, Z_{DR}, and the specific differential propagation phase shift, K_{DP}, have been tested. The rain rate estimators are further combined with an attenuation correction scheme. A comparison between radar and rain gauge indicates that Z_{DR} based rain rate algorithms show an improvement over the traditional Z-R estimate. K_{DP} based estimates do not provide reliable results, mainly due to the fact, that the observed K_{DP} parameters are quite noisy. Furthermore the observed rain rates are moderate, where K_{DP} is less significant than in heavy rain.

1 Introduction

In contrast to conventional weather radars, where the reflectivity is measured in one polarization plane only, a dual polarization radar provides transmission in either horizontal, vertical, or both polarizations while receiving both the horizontal and vertical echoes simultaneously. The back-scatter from precipitation particles is different for horizontal and vertical polarization, as the particles are generally non-spherical. Information on size, shape, and material density of precipitation particles is obtained by comparing the reflected horizontal and vertical power returns and their ratio and correlation.

This principle of dual-polarization weather radar measurements is well known since many years, e.g. by studies of McCormick and Hendry (1975) or Seliga and Bringi (1976), but apart from several research radars, operational C-band weather radars with dual-polarization are available since few years only. The new Austrian C-band weather radar is therefore among the first operational C-band radars equipped with dual-polarization capabilities. It is located in the western part of Austria at the border between the provinces Vorarlberg and Tyrol and is intended to improve radar coverage over this alpine region and to provide quantitative rainfall estimates for meteorological, hydrological and natural hazards applications. The chosen radar site is on the top of Mt. Valluga in an altitude of 2809 m a.m.s.l.

The new weather radar is equipped with an ortho-mode feed and electronically controlled waveguide signal routing to provide transmission in either horizontal, vertical, or (simultaneously) both polarizations, while receiving both the horizontal and vertical echoes simultaneously by two separate receiver units. A mode change from simultaneous transmission to either vertical or horizontal transmission is required for Linear Depolarization Ratio (LDR) measurement.

Operating a weather radar in an alpine terrain is challenging not only in terms of radar maintenance, but also concerning the implementation of algorithms for rainfall estimation. In order to provide a good coverage over a large area and to avoid blocking of complete sectors, the radar has to be situated on top of a mountain. As a result of volume scanning in high altitudes, low altitude rainfall is sometimes missed. The high location is also close to the freezing point, where precipitation can occur not only in liquid, but also in frozen or mixed phase state. These conditions make it difficult to get an accurate rainfall estimation on the ground. To overcome these problems a scanning strategy including negative elevations can be used, but scanning with negative elevations

Correspondence to: H. Paulitsch
(helmutp@radar.tugraz.at)

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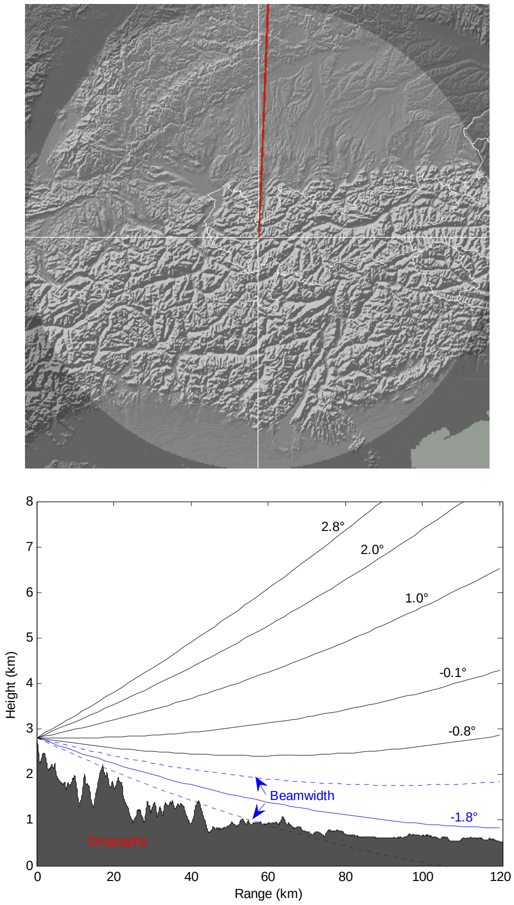

Fig. 1. (a) Location of the Valluga weather radar (in the center of the crosslines) (b) Beam height above mean sea level over range for different elevation angles. The orography profile is given for the red line in (a).

generally leads to more clutter echoes and can be limited in range by partial or total beam blockage due to surrounding mountains. Figure 1 shows the location and the elevation levels of the Valluga weather radar. It can be seen that the lowest beam at -1.8° elevation is affected by partial beam blockage and ground clutter. An example of beam blockage and ground clutter can be seen in Fig. 2, which shows six PPI scans of reflectivity at elevation angles between -1.8 to 2.8 degrees. Especially at -1.8° elevation the echoes at a distance farther than 60 km are strongly affected by ground clutter.

2 Dual polarization parameters

In a preparation phase before the start of the routine operation in October 2007 different scanning strategies have been tested and dual polarization radar data have been collected. Due to operational requirements only the simultaneous transmission mode was used and therefore no LDR parameter is available. Several volume scans recorded between 23 August and 29 August have been further investigated. Each of the volume scans was sampled in 14 different elevations with a one degree resolution in azimuth, a range bin length of 125 m and a range of 120 km. The detailed radar characteristics are summarized in Table 1.

Table 1. Characteristics of the Valluga radar during test run.

Altitude	2809 m (MSL)
Frequency	5.625 GHz
Beamwidth	0.95°
Transmitter type	Coaxial magnetron
Peak power	250 kW
Pulse length	0.8 µs
Pulse repetition rate	$1000\,\mathrm{s}^{-1}$
Samples per integration	50
Rotation rate	4 RPM (24°/s)
Range resolution	125 m
Number of range-gates	960
Maximum range	120 km
Elevation angles	14 from -1.8° to +90° (-1.8, -0.8, -0.1, 1.0, 2.0, 2.8, 4.2, 7.7, 10.2, 13.7, 19.7, 30.2, 60.0, 90.0)

One of the fundamental variables in dual-polarization systems is the differential reflectivity Z_{DR}, which is the ratio of the horizontal and vertical power returns

$$Z_{\mathrm{DR}} = 10 \log\,(Z_{\mathrm{H}}/Z_{\mathrm{V}}) \tag{1}$$

and is expressed in dB. Z_{DR} is dependent on particle properties, such as the shape of rain drops. If the majority of the particles in the measured radar volume have a non-spherical shape, and polarization is aligned with the particle axes, the power return will be greater for one polarization than for the other. For large rain drops with an oblate shape, the horizontal power return will be greater than for the vertical and therefore the Z_{DR} value will be positive. Small rain drops or light hail particles are more like spheres and result in Z_{DR} values near one or zero dB. Negative dB values can occur for large hail with conical shape.

Examples of Z_{DR} measurement at several elevation angles are shown in Fig. 3. The lowest elevation with -1.8 degrees is clearly dominated by beam blocking and clutter echoes, and there is a certain degree of noise visible in all elevations. In areas with moderate rain (reflectivity Z_{H} from 20 to 30 dBZ), the measured Z_{DR} values are quite high and reach values of 5 dB and more. Such high values have been measured at all elevations. However, in rain Z_{DR} is expected to decrease with increasing elevation and become 0 dB at 90° elevation, since rain drops appear spherical in vertical direction (under the assumption that there is no canting angle of the drops due to winds). With the Valluga radar in rain an

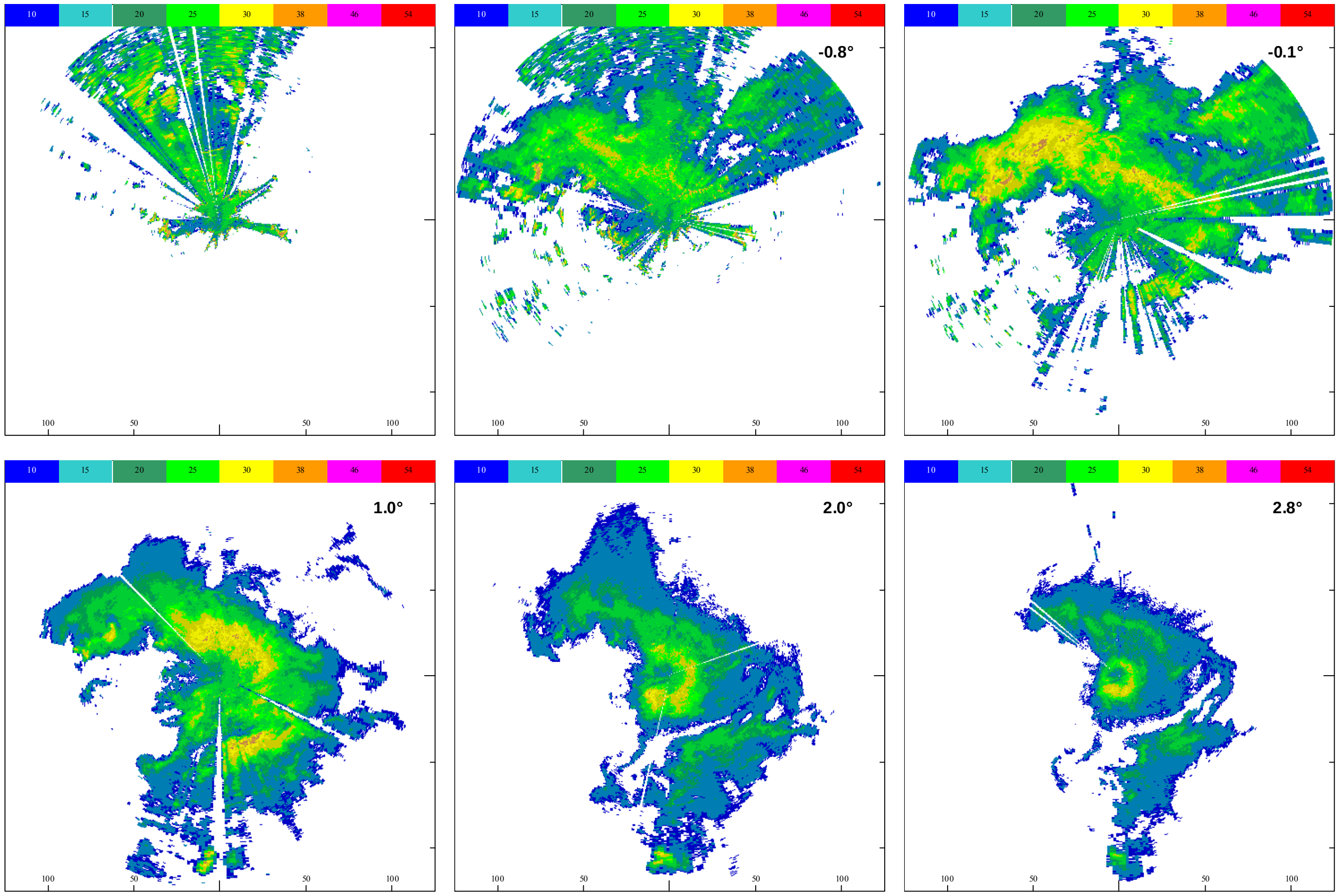

Fig. 2. PPI scans of Z_H [dBZ] at various elevation angles from $-1.8°$ to $2.8°$ (28 August 2007, 08:37 UTC). Max. range 120 km. Narrow white sectors are due to beam blocking or non-optimal signal processing.

average Z_{DR} of 3.1 dB at 60° and an average Z_{DR} of 2.5 dB at 90° elevation was measured. This indicates that there is a systematic bias in the measurement of Z_{DR}.

The correlation coefficient, ρ_{HV}, is a measure of the correlation between the reflected horizontal and vertical co-polar power returns. Generally in rain the correlation is high and ρ_{HV} is close to one. In regions where there is a mixture of precipitation types, such as rain and snow, or where the particles are highly irregular, the correlation is much lower and can result in ρ_{HV} values down to 0.8, for example for wet snow. These conditions occur in the bright band, when frozen particles begin to melt with increasing temperature. The profile of ρ_{HV} along an elevated radar beam is therefore a good indicator for the beginning and the end of the bright band.

In the examples shown in Fig. 4 this behavior can be seen. In the first two PPI scans with negative elevations the correlation is about 0.98 around the radar and only decreases at greater distances, whereas in scans at higher elevations a ring structure of low correlation is visible. Beam heights corresponding to the low ρ_{HV} are between 3000 and 3500 m. It is indeed striking, that there are large (white) areas without any correlation at all, partly in areas with low reflectivity and at larger distances, but probably also caused by noise from ground clutter echoes.

The differential phase shift, φ_{DP}, is the phase shift that occurs between the horizontally and vertically polarized pulses along the propagation path. The phase shift is caused by variations in the wave propagation speed, when the electromagnetic pulses encounter precipitation particles of different sizes and shapes. The range derivative of the differential phase φ_{DP} is called the specific differential phase, K_{DP}.

Since the phase shift is not influenced by propagation effects like attenuation or beam shielding, which reduce the power return, it can be used for attenuation correction. K_{DP} is also a good estimator of rain rate, especially at high rain rates. While the phase shift is a variable measured by the radar, K_{DP} is derived from φ_{DP} and special care has to be taken, as an improper construction of the φ_{DP} profile can lead to unreliable K_{DP} values. Phase measurements are quite noisy and require filtering and combining of several range gates to retrieve useful results. Analyses of the test data have shown, that it is indeed problematic to derive K_{DP} and averaging over at least 40 range gates (5 km) is needed to gain reasonable results. It has also turned out, that the resolution

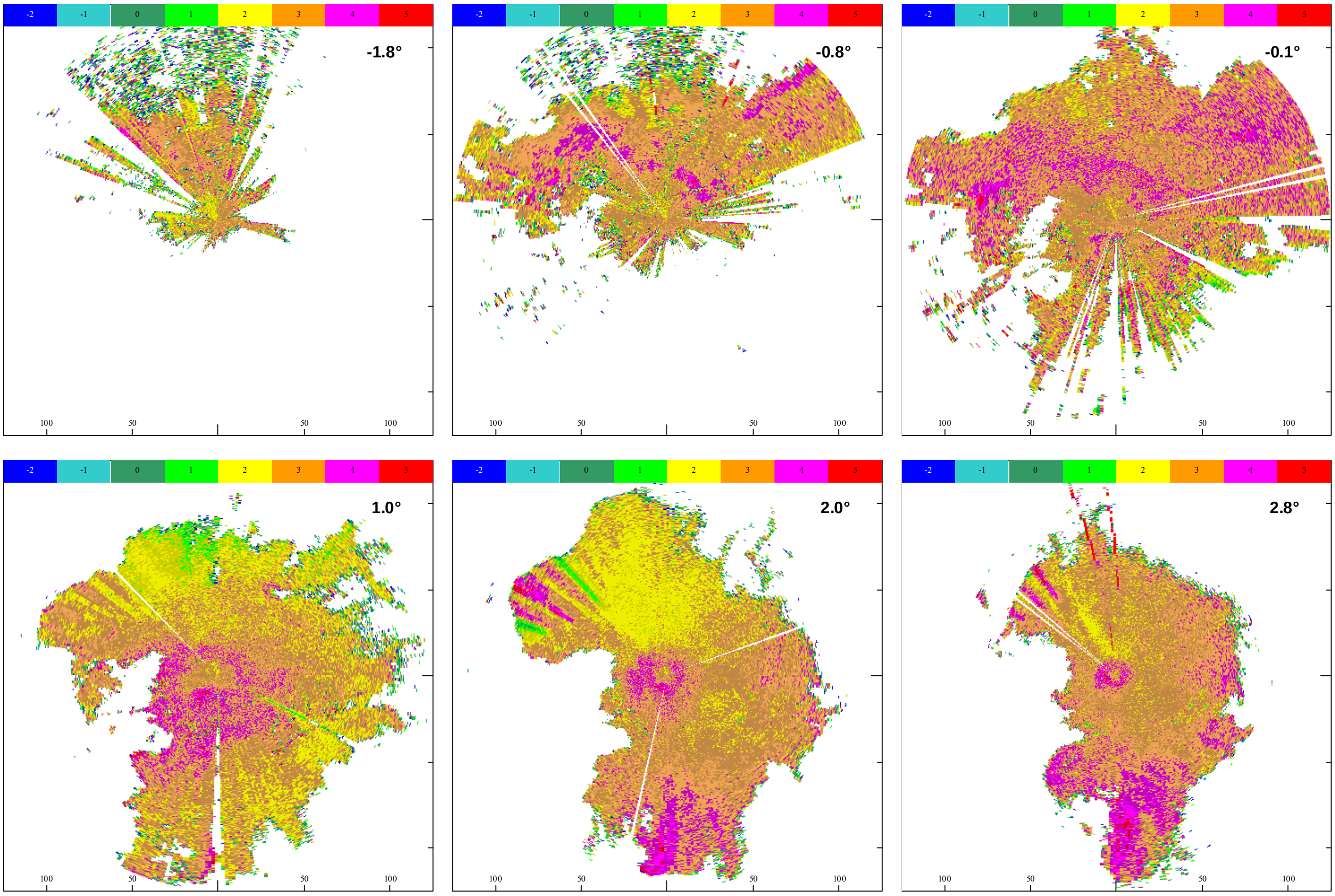

Fig. 3. PPI Scans of Z_{DR} [dB] at various elevation angles from $-1.8°$ to $2.8°$ (28 August 2007, 08:37 UTC).

of the phase measurement as provided by the radar software occurs in multiples of 1.4 degrees, one reason that makes it difficult to derive reliable K_{DP} values.

At the elevation of the radar precipitation often occurs in solid or in mixed phase form and even in the alpine summer low scanning elevations are in or just below the bright band. As a consequence the radar beam often contains nonuniform precipitation in both solid and liquid form. Nonuniform beamfilling however, decreases the quality of polarimetric radar variables considerably. This effect increases with the range due to the progressive broadening of the beam. Nonuniform beamfilling can especially cause "significant perturbations on the radial profile differential phase φ_{DP}" (Ryzhkov, 2006). This effect could also be observed with the present data and eventually is manifested in negative values for K_{DP} (cf. Ryzhkov and Zrnic, 1998).

The examples in Fig. 5 show only low phase differences usually not exceeding 45 degrees over 100 km. A detailed view of single beams show that φ_{DP} is more or less constant for the first few kilometers (light rain) before it decreases (beginning of bright band) and then slowly increases at a rate 0.5 degree/km once the bright band region is passed (Fig. 6). The bright band effect is visible on all parameters, by a strong increase of Z_H, a drop of ρ_{HV}, a small change in φ_{DP}, and an increase in Z_{DR}.

3 Attenuation correction

Attenuation along the propagation path in precipitation can degrade radar measurements to a considerable degree. In order to make accurate rainfall estimates, an attenuation correction scheme for Z_H and Z_{DR} should be used. Studies by Bringi et al. (1990) and Smyth and Illingworth (1998) suggest different correction methods for attenuation in rain. The following relations from Bringi and Chandrasekar (2001) show a nearly linear relation between attenuation factors and K_{DP}:

$$A_H = 0.073 K_{DP}^{0.99} \quad (2)$$

$$A_{DP} = 0.013 K_{DP}^{1.23} \quad (3)$$

where A_H is the specific attenuation in dB/km for horizontal polarization, A_{DP} is the specific differential attenuation in dB/km and K_{DP} is the specific differential phase in deg/km.

Considering the described challenge to derive reliable K_{DP} values from φ_{DP}, and the fact that iterative approaches show

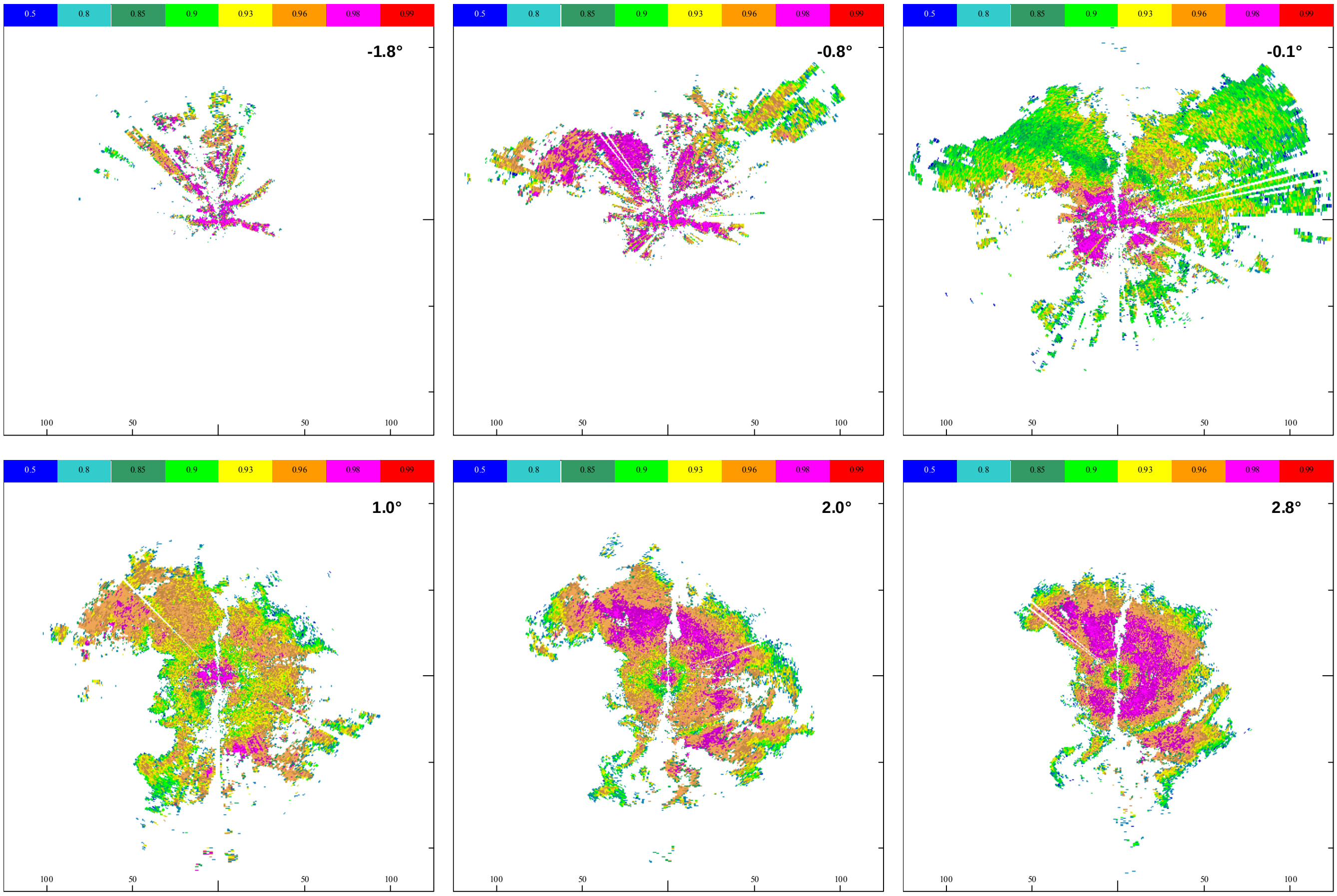

Fig. 4. PPI scans of ρ_{HV} at various elevation angles from $-1.8°$ to $2.8°$ (28 August 2007, 08:37 UTC).

a tendency to lead to unstable and unrealistically high results, the following, more conservative approach is used:

$$A_H = 0.05 K_{DP} \tag{4}$$

$$A_{DP} = 0.01 K_{DP} \tag{5}$$

These correction factors are among the lowest that can be found in literature (Bringi and Chandrasekar, 2001, p. 494). The linear relationship also allows calculating the attenuation at a certain range-gate directly from the differential phase shift.

While attenuation in rain is well understood, there is little experience of attenuation effects in mixed phase or solid precipitation. Since the weather radar at 2809 m senses solid precipitation often during the course of the year, the use of attenuation correction factors dedicated for rain is questionable.

In the test data only moderate rainfall occurred where attenuation is not a real issue anyway. The highest φ_{DP} values found in the available data sets are about 70 degrees in 80 km distance from the radar, while the majority of values does not exceed 45 degrees. Derived K_{DP} values are usually between zero and 2°/km, with an average of about 0.4°/km. Based on these numbers attenuation correction results are a maximum of 1.75 dB for Z_H and 0.35 dB for Z_{DR} and 1 dB and 0.2 dB respectively on average. One should keep in mind, that these results are for solid or mixed phase precipitation, and the attenuation in light rain only is insignificant in these examples.

Figure 7 illustrates the polarimetric parameters along a beam at $-0.8°$ elevation. The figure also shows the filtered curve of φ_{DP} and the thus corrected reflectivity Z_H according to Eq. (4). Starting at a range of about 45 km the correction becomes noticeable and sums up to about 1.5 dB due to a sharp increase of φ_{DP} and K_{DP} respectively.

4 Rain rate estimation

In addition to a traditional Z-R relationship relying on Z_H alone, the specific differential phase (K_{DP}) and the differential reflectivity (Z_{DR}) are applied in rain rate algorithms of polarimetric weather radars. A detailed evaluation of these rainfall algorithms is given by Bringi and Chandrasekar (2001). The typical form of these estimators is:

$$R(K_{DP}) : R = \mathrm{a}\ K_{DP}^{\mathrm{b}} \tag{6}$$

$$R(K_{DP}, Z_{DR}) : R = \mathrm{c}\ K_{DP}^{\mathrm{a}} 10^{(0.1\mathrm{b}\ \mathrm{ZDR})} \tag{7}$$

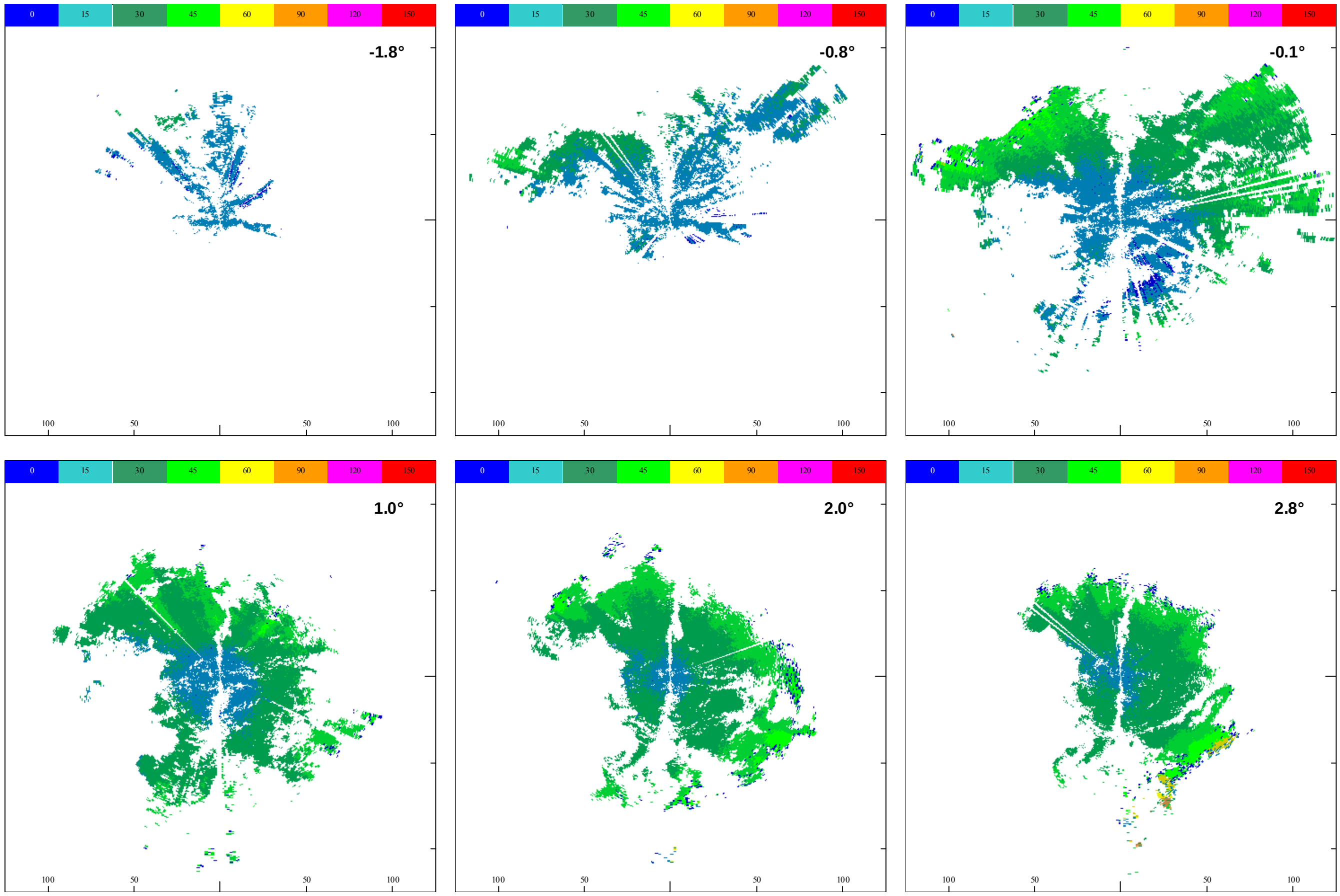

Fig. 5. PPI scans of φ_{DP} [degree] at various elevation angles from $-1.8°$ to $2.8°$ (28 August 2007, 08:37 UTC).

$$R(\mathrm{Z_H}, Z_{\mathrm{DR}}): R = \mathrm{c}\ Z_{\mathrm{H}}^{\mathrm{a}} 10^{(0.1\mathrm{b\ ZDR})} \tag{8}$$

where R is the rain rate.

In a previous study (Teschl et al., 2008), polarimetric radar variables were simulated for S-, C- and X-band wavelengths in order to establish radar rainfall estimators in an alpine region in the form $R(K_{\mathrm{DP}})$, $R(\mathrm{Z_H}, Z_{\mathrm{DR}})$, and $R(K_{\mathrm{DP}}, Z_{\mathrm{DR}})$. Drop size distributions of hundreds of 1-min-rain episodes were obtained from 2-D-Video-Distrometer measurements in the mountains and were used as input of the simulation. Also the influence of different rain drop shape models was investigated. Assuming the model of Brandes et al. (2002) the C-band rain rate estimation algorithms are

$$R(K_{\mathrm{DP}}): R = 18.77\ K_{\mathrm{DP}}^{0.769} \tag{9}$$

$$R(K_{\mathrm{DP}}, Z_{\mathrm{DR}}): R = 22.4\ K_{\mathrm{DP}}^{0.77} 10^{-0.072\mathrm{ZDR}} \tag{10}$$

$$R(Z_{\mathrm{H},} Z_{\mathrm{DR}}): R = 0.015\ Z_{\mathrm{H}}^{0.82} 10^{-0.290\mathrm{ZDR}} \tag{11}$$

with R in mm/h, Z_{DR} in °/km, Z_{H} in mm^6 m^{-3} and K_{DP} in dB.

Several data samples from the available data sets were used to test these estimators. These samples were carefully chosen from areas with rainfall and any data from the bright band was avoided. The samples included horizontal reflectivity values between 14 and 32 dBZ. From the observations of Z_{DR} and K_{DP} made before, it was clear that the uncorrected data will not produce any useful results. Z_{DR} was therefore corrected by an estimated offset of -2.5 dB. There was no success at all with the K_{DP} estimators, as reliable values of K_{DP} could not be calculated for the selected measurements of moderate rainfall.

Figure 8 shows a comparison of the rain rates $R(Z_{\mathrm{H}})$ and $R(Z_{\mathrm{H}},\ Z_{\mathrm{DR}})$ for 20 selected samples obtained at different locations with the rain rate measured by a rain gauge in this area. To calculate $R(Z_{\mathrm{H}})$ the standard relationship $Z = 200\ R^{1.6}$ was used; $R(Z_{\mathrm{H}},\ Z_{\mathrm{DR}})$ is given in Eq. (10). The standard relationship leads to a root mean squared error (RMSE) of 1.09 mm/h and overestimates the rain rate considerably with a mean value of 1.14 mm/h. The RMSE of the $R(\mathrm{Z_H},\ Z_{\mathrm{DR}})$ estimator is 0.19 mm/h and the mean value of 0.36 mm/h is close to the gauge measurement of 0.3 mm/h. This $\mathrm{Z_H} - Z_{\mathrm{DR}}$ based rain rate estimator therefore shows an improvement over the standard Z-R relationship for the selected data sets, which include light and moderate rainfall events only – heavy rainfall events have not been recorded during the analyzed period.

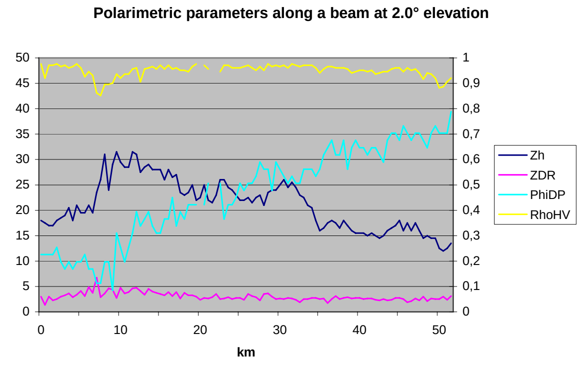

Fig. 6. Polarimetric variables along a single beam at 2.0° elevation.

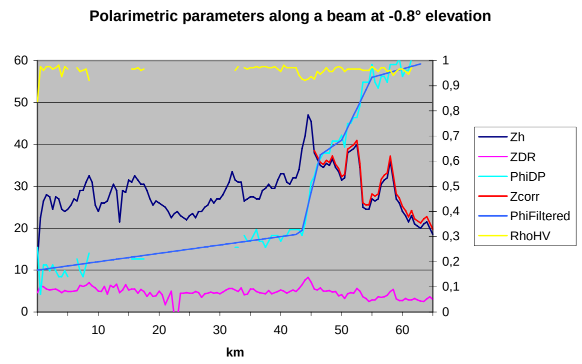

Fig. 7. Polarimetric variables along a single beam at −0.8° elevation, including filtered PhiDP and attenuation corrected Zh.

5 Conclusions

This study presents dual-polarization observations of precipitation events during a test phase of the new C-band dual-polarization weather radar on Mt. Valluga, Austria. Since the radar is located at more than 2800 m above MSL, precipitation even in summer often occurs in solid or in mixed phase form. Nonuniform beamfilling therefore is common and decreases the quality of polarimetric radar variables considerably. The analysis shows, that the polarimetric parameters in the available data sets are quite noisy and also include offsets. Further the lowest elevation (−1.8°) is affected considerably by ground clutter at distances farther than 60 km.

For the attenuation correction based on K_{DP} a conservative approach was used mainly due to the frequently sensed mixed phase precipitation. Further the analyses showed that K_{DP} has to be averaged at least over 5 km (40 range gates) to obtain useful results.

Finally for the rain rate estimation an algorithm based on Z_H and Z_{DR} seems most promising, while algorithms based on K_{DP} are not applicable at low and moderate rain rates.

For further use of polarimetric data it seems therefore necessary to improve the quality of the data by using advanced clutter filtering techniques and an accurate radar calibration.

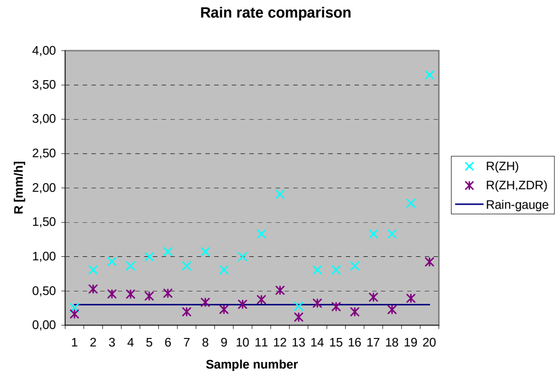

Fig. 8. Comparison of rain rate estimates at 20 locations, together with value measured on the ground.

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