Rain rate retrieval of partially blocked beams from single-polarized weather radar data

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1 Introduction

For quantitative precipitation estimation (QPE), the lowest sweep (base-level scan) of a weather radar is the most important one that contains usually the most valuable information, since it measures the reflectivity nearest to the ground. This way, effects such as overshooting, vertical reflectivity gradients, wind drift or subcloud evaporation (Kitchen and Jackson, 1993) are minimized. At the same time the lowest elevation angles are particularly prone to ground clutter and beam blocking. The latter results when the radar beam is partially intercepted by an obstacle that leads to a reduction of the received power from possible hydrometeors at ranges beyond the obstacle. This implies an inherent trade-off, scanning as low as possible and as high as necessary (Smith, 1998). For that reason the German Weather Service (DWD) introduced a scan strategy that follows the terrain surface in base-level scan mode.

But in many cases the demand for exposed positions of weather radar stations compete against the interests of broadcast towers in immediate vicinity. For these special cases even higher elevation angles are partially blocked within certain azimuthal sectors. Thus a substitution by the lowest (but still very high) unaffected elevation is of great uncertainty. An prominent example is the location of radar station Feldberg in the vicinity of the SWR (Southwest Broadcasting) tower on top of the mountain Feldberg (1493 m) in the southwest of Germany situated in direct proximity (Fig. 1).

Figure 1:Top of mountain Feldberg with its radar station and SWR tower. The point of view deludes a shorter distance than 158 m to each other. Adopted and edited from http://de.wikipedia.org/wiki/Sender_Feldberg.

In a plan position indicator (PPI) of the annual rain amount (Fig. 2), the partial beam blockage becomes apparent in a confined sector at about 135°, where the intensity decreases suddenly over several degrees as compared to the adjacent azimuths (Helmert et al., 2012). A sector of approximately 6° is affected by partial beam blockage. Even only assuming a measuring range of 100 km for QPE, this corresponds to a contiguous area of 500 km^2 without reliable data.

On closer inspection the seeming noise from all beams in the partially blocked sector was identified as a weak signal that is strongly correlated to the adjacent unaffected beams.

Physically based sophisticated reflectivity corrections would require very accurate surveys of elevation and azimuthal orientation of the antenna. Small differences to the actual orientation can provoke unacceptable errors, since the correction term grows exponentially with the increasing degree of shielding.

Based on this consideration, a straightforward, robust and rather heuristic approach was developed to reconstruct the reflectivity in this sector. The beam averages of the two unaffected edges of the partially blocked sector are interpolated over the partially blocked sector and their ratio to the corresponding averages of the partially blocked beams is assumed to be the correction factor.

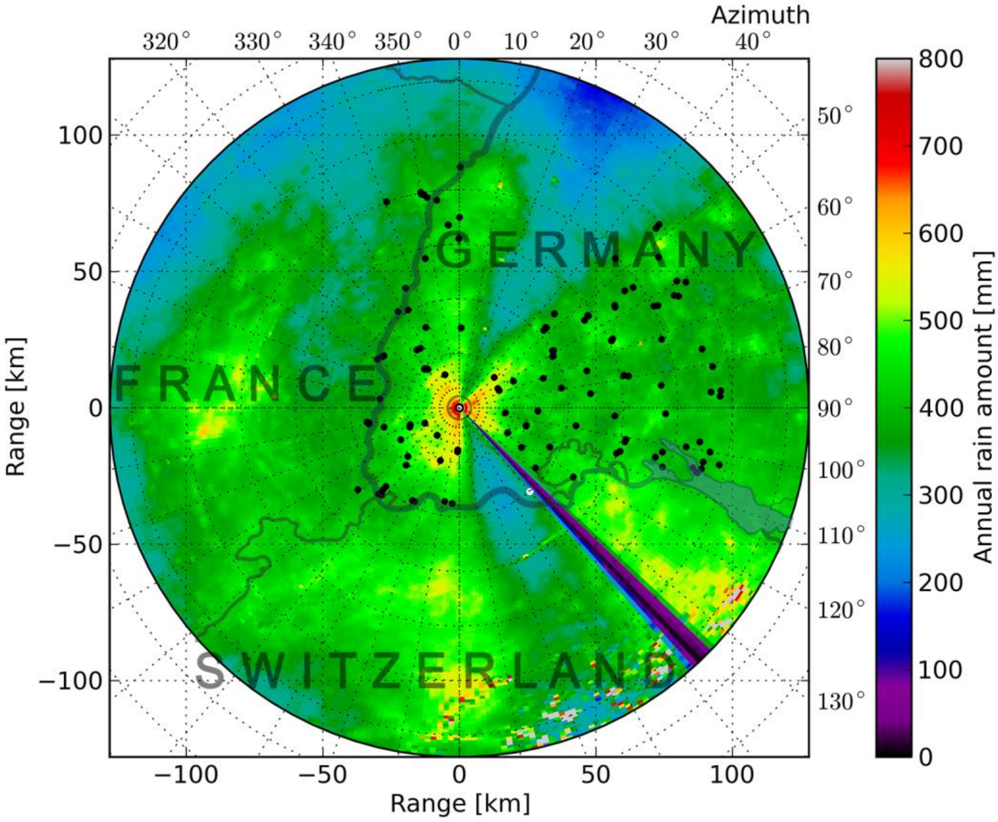

Figure 2: PPI of the accumulated rain amount over one year (5/2008-4/2009) without any corrections (raw-data converted with Marshall-Palmer ZR-relation); Black dots represent rain gauges; white dot is rain gauge station Küssaburg near the partially blocked sector.

Commonly shielding effects are corrected on the basis of static correction factors achieved by the difference of longtime averaged radar and rain gauge measurements or by vertical profile of reflectivity based extrapolation of higher elevation measurements. The former methods do not allow for specific meteorological situations, the latter ones do not use the information contained in the partially blocked reflectivity data (Hannesen, 1998). Besides, it is very ambiguous to extrapolate from very high elevation angles to a base-level elevation. As far as we know no attempt has been operationally undertaken to correct for well-known partially blocked sectors based on their inherent reflectivity information.

The purpose of this paper is to present a post-processing technique of successful rain rate retrieval in special cases of partial beam blockage based on a self-consistent approach for single-polarized radar observations. To validate the results the rain accumulations between radar measurement and rain gauges were compared. According to the narrow area of shielding and the proximity to the German border, there was only one gauge available for validation.

The correction scheme was applied in two cases covering a stratiform and a convective precipitation type event and a longterm accumulation of one year. To validate the results against unaffected beams, the radar rain accumulations were compared to hourly measuring rain gauges.

Other sources of error such as attenuation of precipitation and wet radome, uncertain Z-R-relationship or variable vertical profiles of reflectivity (VPR) are ignored in this study.

Section 2 provides an overview of the data sources. Section 3 describes the correction methodology. The results are reported in section 4 and discussed in section 5.

2 Data

2.1 Radar

Radar station Feldberg (lat.47°52’28’’ N, lon. 08°00‘18‘‘ E) is the southernmost part of a network of currently 17 C-band (5.64 GHz) radar stations operated by the DWD. In the analyzed period of 2008-2009 all radars (back then 16) were equipped with single polarized Doppler technology. The base-level scan - in DWD terminology “precipitation scan” – is repeated every five minutes with an azimuthal resolution of 1°, a measuring range of 128 km, subdivided into 128 range gates and a terrain-following variable elevation angle. The data are preprocessed at the radar’s signal processor in order to conduct a first quality control e.g. Doppler filtering for stationary clutter suppression (Seltmann, 2000). For all further radar data processing steps and visualizations we used *wradlib*, an open source library for weather radar data processing (Heistermann et al. 2013).

The elevated position of radar station Feldberg allows for base-level scan elevation angles (0.1 - 0.4°) below half of the beamwidth. Figure 2 shows in the south to south-east direction a lot of Alpes-clutter arises beyond 100 km distance and interestingly two further not as obvious effects of partial beam blockage can be seen at the azimuthal sectors 15-45° and 140 - 170°, respectively. Both occultations arouse from the additional vertical aligned antennas at the radar tower that can be seen in Figure 1.

Inspite of the internal clutter treatment as described before partially blocked beams can be contaminated by clutter remnants, which can evoke large errors in correction. For this reason the rain rate retrieval is followed up with a clutter detection algorithm proposed by Gabella and Notarpietro (2002) and a nearest neighbour interpolation for masked range gates.

2.2 Rain Gauges

Precipitation data was accumulated at hourly intervals for 126 rain gauges inside the radar scanning area (Fig. 2). These were used to compare the performance of the partial beam blockage correction with the remaining scanning areas. The selection of gauges was restricted by choosing only gauges situated in the range between 10 and 100 km from the radar antenna and excluding gauges within the very wide partially blocked sectors in the NNE and SSE. The white dot in Figure 2 about 40 km in the SE of the radar station remarks the gauge Küssaburg, which is nearest (1 km) to the center of a range gate in the partially blocked sector and thus used for evaluation there.

3 Method

Figure 3 illustrates the correction scheme. For interpolation and averaging purposes the reflectivity (Z in [$mm^6\ m^{-3}$]) is converted to rain intensities (R in [$mm\ h^{-1}$]) at first (Fig. 3a). The conventional Z-R-relationship with

$$Z = 200R^{1.6} \qquad (2.1)$$

found by Marshall and Palmer (1948) is used.

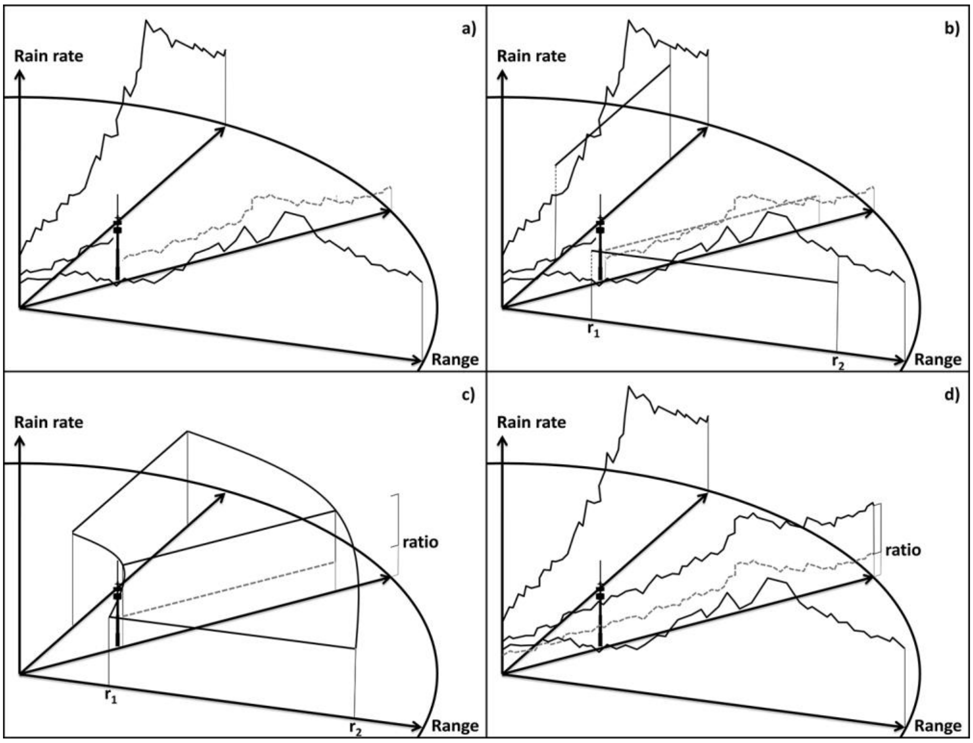

Figure 3: Correction scheme for partially blocked beams. Data are (a) converted to rain intensity, (b) averaged over a certain range r_1-r_2 using distance weights; (c) averages of the unaffected framing beams are interpolated to the partially blocked beams and ratios between interpolated averages and averages from partially blocked beams are calculated; (d) ratios are used as beamwise correction factors for partially blocked range gates.

The rain intensities of the partially blocked beams as well as the framing unaffected beams are averaged starting from the range gate beyond the obstacle but at least 10 km away from the antenna and ends at the maximum radar range but not exceeding 100 km (Fig. 3b). These range limitations consider the most reliable range of radar measurements (Kitchen and Jackson, 1993; Krajewski and Smith, 2002). The average is weighted by the inverse distance between the gates and the radar antenna. This means the highest weights are assigned to the nearest gates.

Afterwards the framing beam averages are interpolated in the partially blocked sector. Then the ratio between the interpolated averages and their corresponding averages of the partially blocked beams are calculated for each beam in the sector (Fig. 3c).

These beamwise ratios are then used as correction factors for the beams in the partially blocked sector beginning with the range gate beyond the obstacle (Fig. 3d). This way the beam is amplified as a whole without losing consistency of values along the radar beam.

4 Result

The presented partial beam blockage correction approach was tested on a convective as well as a stratiform rain event and over a contiguous period of one year.

On 30 May 2008 a convective system developed in the area of the partially blocked sector. For the 6-h period between 1600 and 2300 CET rainfall accumulations were compared between radar data as received from radar station (Fig. 4a) and data that were corrected for partial beam blockage (Fig. 4b). From visual inspection the corrected image appears consistent and plausible in contrast to the uncorrected origin. Unfortunately the correction did not have much of an impact for the beam with its center at 138.5° near the gauge (black circle at 140°, 40km away from radar station). Thus, the corresponding scatter plot (Fig 5a) of radar and rain gauge accumulations is almost identical for the corrected (black) and the uncorrected (gray) radar data.

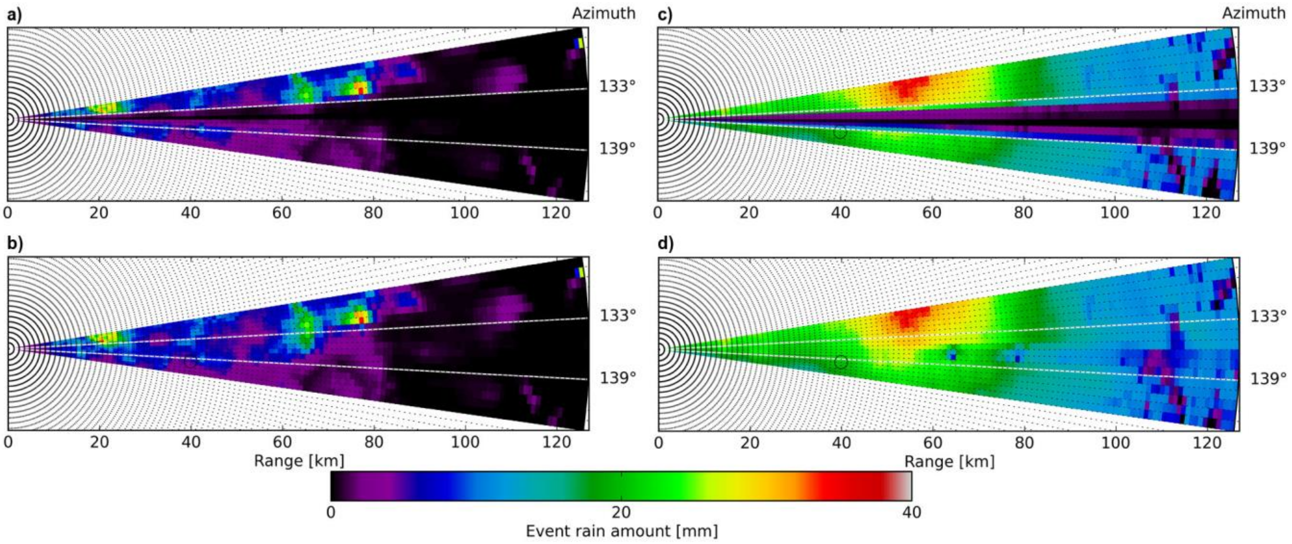

Figure 4: 6-h rain accumulations of a convective rain event (a) without and (b) with correction for partial beam blockage and 71-h rain accumulation of a stratiform rain event (c) without and (d) with correction for partial beam blockage; partially blocked sector is located between the two white lines; black/white circle marks the rain gauge used for validation; for space-saving purposes the PPI sectors are rotated 46° counterclockwise.

Since the spatial distribution of rainfall is more homogeneous for the stratiform event, the extreme underestimation of uncorrected radar data becomes more obvious in its extent (Fig. 4c). The event lasted 71 hours beginning on 27 October 2008 at 0900 CET and ending three days later at 0800 CET. The corrected image (Fig. 4d) again appears consistent with the surrounding beams that are not affected by partial beam blockage. But it can be seen that between 136° and 138° the signal amplification is still a little bit insufficient. In terms of clutter, Figure 4d also illustrates the effects of airport Zurich (64 km) and the Alps (beyond 105 km). The comparison of corrected and uncorrected data in the scatter plot (Fig. 5b) indicates an improvement of the QPE.

Both corrected images (Fig. 4b,d) suggest that the assumed consistency between the partially blocked sector and its environmental beams can be evidentiary reconstructed. Surprisingly the beam with the strongest shielding effect seems not to be constant. For the convective event it concerns the beam with the azimuthal center at 135.5° in contrast for the stratiform event where it is the 136.5° beam.

The rainfall accumulation over one year in the radar – rain gauge scatter plot (Fig. 5c) clearly shows the improvement of the precipitation estimates. It has to be considered that the compared range gate is one of the less shielded in the border area of the partially blocked sector. For the central beams the improvement is supposed to be much better but hard to prove due to absent data for ground truthing.

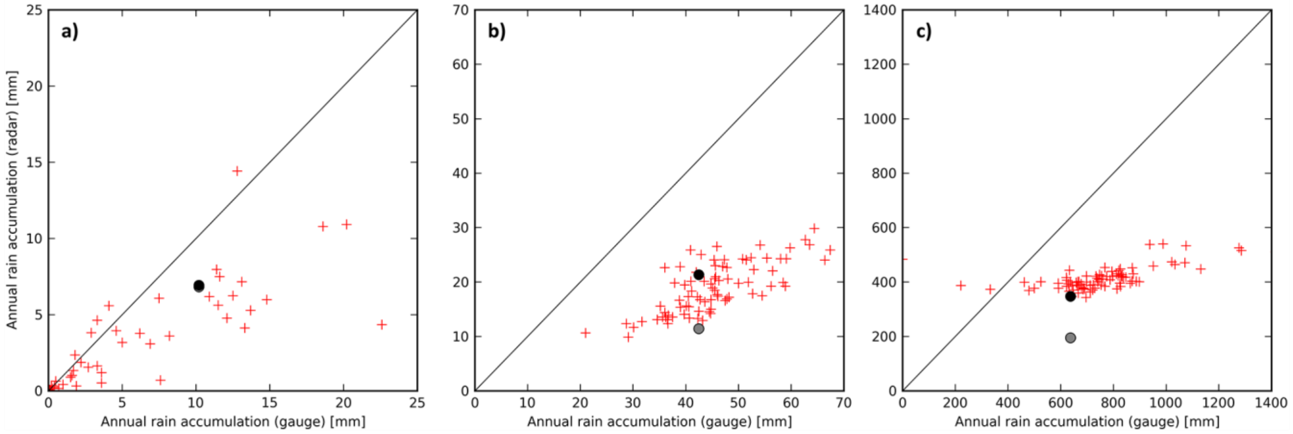

Figure 5: Scattergram of rain accumulations obtained from radar and rain gauge (a) for a 6-h convective rain event, (b) a 71-h stratiform rain event and (c) an rain accumulation over one year; gray dot marks the scatter pair with the uncorrected and black dot the corrected range gate.

Figure 6 presents the rain amount over the same year along the partially blocked (gray dashed lines) and the corrected (black solid lines) beams and their relation to the adjacent unaffected beams (red solid lines). It is apparent that the rain amount is underestimated due to the partial beam blockage. Depending on the beam the bias ranges from factor 1.2 up to 25 in rain rate, which corresponds to 1-22 dB in average for the reflectivity, respectively. Considering that the corrected beams are just adapted with one factor along the whole beam the variations along the beams and their unaffected immediate neighbors are in good correlation. But obviously there are difficulties in estimation at the distance of 64 km and beyond about 105 km where the Airport Zurich lies and the Alps begin, respectively. Just as well as the deviations at 80 km, that can be seen in Figure 4d, too.

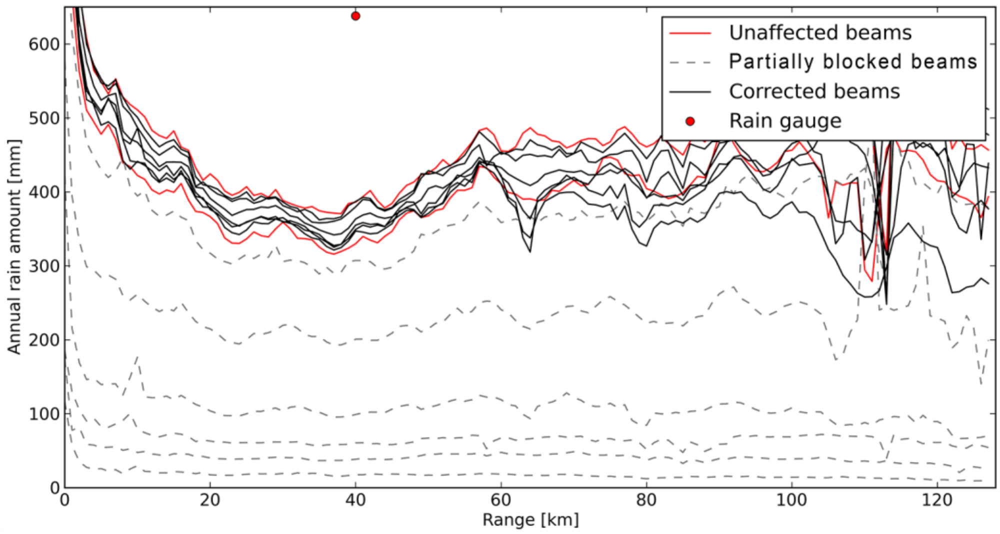

Figure 6: Selected radials of annual rain amount (5/2008-4/2009) of radar station Feldberg.

5 Discussion

Based on the analysis of two events and a long term accumulation, the correction of partial beam blockage increases both the consistency with unaffected radar beams as well as with rainfall observations by rain gauges. Due to its simplicity and fast computation speed, this correction scheme is well suited for real-time QPE. According to the remaining difference between radar and gauge measurements in the Figures 5 and 6 further processing steps are necessary to improve the quality of the precipitation estimates, such as attenuation correction, VPR correction and rain gauge adjustment.

The advantage of the correction scheme is that it only requires the instantaneous scan data (although affected beams should be manually selected). This way we can also account for the fluctuation of the beam with the strongest shielding effect (Fig. 4a,c). The correction is not based on vertical extrapolation or horizontal interpolation, but consistently amplifies the residual signal.

An imaginary regression line in the scatter plot of the annual rain accumulation (Fig. 5c) misses the origin by far. That means the radar measurements flatten the spatial heterogeneity of annual precipitation. The reason for that effect was not investigated.

Though the framing beam at 139.5° used for interpolation of the beam averages is unaffected by the partial beam blockage of the SWR-tower, it is in turn affected by the less intensive but broader partially blocked sector in the SSE (Fig. 2) caused by the antenna on the radar tower (see Sec. 2.1). This situation inhibits the full potential of the correction procedure. In Figure 6 this effect can also be seen in the nearly constant difference between the two red lines. From that aspect the lower red line is technically speaking not really unaffected by partial beam blockage.

Furthermore the validation of the correction is difficult since there are no gauges in the central part of the partially blocked sector. Supposedly a comparison of overlapping radar measurements would be a helpful alternative. In that case the radar station "Albis" nearby Zurich would fit the requirements.

Recently, the DWD has finished the replacement of all German network radars by state-of-the-art dual polarization Doppler radars. So it seems to be available to overcome the problem of partial beam blockage with help of specific differential phase measurements since they are immune to beam blockage as long as a portion of the beam is clear from the obstacle (Zrnić and Ryzhkov, 1996) and the signal-to-noise ratio allows a maintainable degree of uncertainty. If this is not the case it should be tested if the horizontal reflectivity data of the dual-pol radar are appropriate as well as the single-pol for the application of the presented correction scheme. Unfortunately after launch of operation of the dual-pol radar system the regarding sector is completely masked up to the elevation of 21.8° recently. Even if the rain rate estimation for partial blocked beams based on polarimetric radar measurements is superior that based on single polarization measurements, the discussed correction approach is important and valuable for the reanalysis of about 12 years of single-pol data.

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