Benchmarking attenuation correction procedures for six years of single-polarized C-band weather radar observations in South-West Germany

Stephan Jacobi and Maik Heistermann
Institute of Earth and Environmental Sciences, University of Potsdam, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany

ABSTRACT
Rainfall-induced attenuation is a major source of underestimation for radar-based precipitation estimation at C-band. Unconstrained gate-by-gate correction procedures are known to be inherently unstable and thus not suited for unsupervised attenuation correction. In this study, we evaluate three different procedures to constrain gate-by-gate attenuation correction using reflectivity as the only input. These procedures are benchmarked against rainfall estimates from uncorrected radar data, using six years of radar observations from the single-polarized C-band radar in South-West Germany. The precipitation estimation error is obtained by comparing the radar-based estimates to rain gauge observations. All attenuation correction procedures benchmarked in this study lead to an effective improvement of precipitation estimation. The first method caps the corrections if the rain intensity increase exceeds a factor of two. The second method decreases the parameters of the attenuation correction iteratively for every radar beam calculation until attaining a stability criterion. The second method outperforms the first method and leads to a consistent distribution of path-integrated attenuation along the radar beam. As a third method, we propose a slight modification of Kraemer’s approach which allows users to exert better control over attenuation correction by introducing an additional constraint that prevents unplausible corrections in cases of dramatic signal losses.

1. Introduction
Rainfall-induced attenuation is a major source of underestimation for radar-based precipitation estimation and particularly pronounced for heavy rainfall. From the perspective of natural hazards research and applications, this is unfortunate: attenuation matters most when we expect the highest benefit from weather radars, i.e. in convective storms that have the potential to trigger urban flooding, flash floods, heavy erosion, or landslide events.

While considered negligible at S-band, attenuation can cause dramatic signal loss with C- and X-band radars. Hitschfeld and Bordan (1954) were one of the first to investigate forward gate-by-gate procedures in order to correct for such losses. They used empirical relations to compute the specific attenuation $A$ from reflectivity $Z$ or rainfall intensity $R$ (see also Olsen et al. 1978; Hendranto & Zawadzki 2003). Path-integrated attenuation (PIA) is then
retrieved by cumulating specific attenuation over the entire propagation path while recursively correcting reflectivity for each gate. This approach has been widely criticized for its instability (by Hitschfeld and Bordan themselves; later by Hildebrand 1978): small errors can grow exponentially over the propagation path, and compromise the entire precipitation estimation procedure. These errors can be caused by artefacts such as ground clutter, by radar miscalibration or by parameter uncertainties in the empirical \( A(Z) \) or \( A(R) \) relations.

Different methods have been suggested to constrain the retrieved PIAT, mostly by considering additional reference observations: the mountain reference technique uses a reference target of known reflectivity at a preferably remote range (Delrieu et al. 1997). Other authors suggested the use of microwave links as attenuation references, either via dedicated research links (Rahimi et al. 2006) or via commercial links from cellular communication backhaul networks (Troemel et al. 2014). For networks with overlapping radar circles, Chandrasekar and Lim (2008) proposed to constrain PIAT by simultaneously solving the set of governing equations for common volumes. And with the advent of radar polarimetry, new approaches were developed to correct for attenuation (e.g. Bringi et al. 1990; Testud et al. 2000; Vulpiani et al. 2008). In particular, the differential propagation phase shift was directly related to the PIAT, and is immune to issues such as radar calibration or partial beam blockage (Ryzhkov & Zrinić 1996).

Irrespective, though, of the potential improvements introduced by radar polarimetry, many weather services in the world still operate single-polarized C-band radars (for Europe, see http://www.eumetnet.eu/radar-network; for the world, see http://wrd.mgm.gov.tr). Even more important, archives of radar observations often reach back more than 20 years and present a unique research asset, e.g. for studying heavy rainfall phenomena, reconstructing historical flood events, or for the emerging field of areal extreme value statistics (e.g. Overeem et al. 2010). Although the consideration of reference measurements such as microwave links has been shown to substantially improve attenuation correction along the corresponding beam, this extra information is, in the vast majority of cases, not available. This is why other (pragmatic) approaches to control instability are still needed in order to address the issue of attenuation in cases of heavy rainfall.

In this study, we benchmarked three gate-by-gate attenuation algorithms over a long verification period of six years. Intentionally, we only investigated algorithms which require no input other than radar reflectivity (no additional information such as microwave links, mountain returns, or overlap with other radars). Instead, we considered algorithms that define rather arbitrary (or pragmatic) constraints in order to enforce stability: the first method follows the approach of Harrison et al. (2000). They proposed to cap PIAT so that rainfall intensity is not corrected by more than a factor of two; the second method described by Kraemer (2008) uses an iterative search procedure in order to optimize the parameters of the \( A(Z) \) relationship. In this context, we will also propose a modification of Kraemer’s approach as a third correction method. The overarching goal of this study is to investigate the behaviour of these three algorithms over a wide range of rainfall conditions, in order to evaluate their effectiveness and robustness for unsupervised processing in both real-time applications and large reanalysis efforts. Benchmarking is done by contrasting the effects of attenuation correction with rainfall that is estimated from uncorrected reflectivity. For this purpose, we use data from a single-polarized C-band radar in South-West Germany, and hourly observations from a relatively dense network of rain gauges. In order to allow for a systematic comparison, the different algorithms were implemented in the open source software \textit{wradlib} (Heistermann et al. 2013). This way, data processing only varied with respect to attenuation correction. In addition, the implementation is transparent and available for other users and developers.

In Section 2, we provide an overview of the study area, the radar and the rain gauge data, the radar data processing and attenuation correction, as well as the verification approach. In Section 3, we first exemplify the behaviour of the attenuation correction algorithms in a case study, and then present the long-term verification results. Conclusions and recommendations are given in Section 4.
2. Data and methods

2.1. Study area and data

Our study area is the very South-West of Germany (Figure 1), a predominantly mountainous region that was repeatedly exposed to severe flash flood events in the past. The C-band radar used in this study is installed on mount Feldberg (1493 m a.s.l.), the highest mountain in the study area. It is part of a network of 17 C-band Doppler radar stations operated by the German Weather Service (DWD) — see Table 1 for further details.

Hourly precipitation depths from 190 rain gauge stations inside the radar scanning area (Figure 1) were used to evaluate the radar-based precipitation estimates. These data were provided by the State Institute for Environment, Measurements and Nature Conservation Baden-Wuerttemberg and the DWD. Both radar and rain gauge data were available over a nearly contiguous period of six years from March 2007 to February 2013.

2.2. Radar data processing

For all the radar data processing steps, we applied wradlib, an open source library for weather radar data processing. All algorithms that used for attenuation correction have been transparently implemented in the wradlib.atten module. wradlib is documented at http://wradlib.bitbucket.org, and a tutorial on how to apply the different procedures is provided at http://wradlib.org/wradlib-docs/latest/tutorial_attenuation.html.
2.2.1. Clutter removal

Despite the application of a Doppler filter at the signal processor, the radar data still contains residual clutter. In attenuation correction, clutter can be a considerable source of instability (Kraemer & Verworn 2008), as the power law relation for specific attenuation is based on signals caused by rain only. Therefore, we applied two additional filters to remove residual clutter before further processing. Both are based on a texture filter that detects strong reflectivity gradients (Gabella & Notarpeitro 2002). The corresponding wradlib function is wradlib.clutter.filter_gabella_a. In order to detect dynamic clutter in each radar image, we adjusted the original filter parameters so that a central bin in a $5 \times 5$ window is marked as clutter if at least 19 bins in that window have a reflectivity of $9 \text{ dBZ}$ less than the central bin. In order to detect static clutter, we applied the filter to an accumulation of the raw radar-based precipitation estimates over the past year (see section 2.2.3 for conversion from reflectivity to rainfall). This filter was also set-up with a window size of $5 \times 5$ bins. The gradient threshold was set to 70 mm.

It should be noted that the clutter filter published by Gabella and Notarpeitro (2002) also contained another step that evaluates the ‘compactness’ of potential clutter phenomena. This part of the filter was not applied in this study.

Reflectivity in range bins that were marked as clutter was interpolated from surrounding bins by inverse distance interpolation with an inverse distance power of 2.

2.2.2. Attenuation correction

The basic forward gate-by-gate correction is originally referred to Hitschfeld and Bordan (1954): the reflectivity in each range gate is recursively corrected for the two-way PIA which is, in turn, retrieved by accumulating the specific attenuation $A$ of each gate over the entire propagation path.

Radar reflectivity $Z$ (mm$^6$ m$^{-3}$), rainfall intensity $R$ (mm h$^{-1}$), and specific attenuation $A$ (db km$^{-1}$) are related via physical rainfall properties such as the number, size distribution, shape, and temperature of the drops as well as the radar wavelength. Except for the wavelength, these quantities are generally unknown. Instead, empirical power law relations have been proposed, both between $R$ and $A$ (e.g. Gunn & East 1954), and between $Z$ and $A$ (e.g. Hitschfeld & Bordan 1954):

$$A = aR^b$$  \hspace{1cm} (1)

$$A = cZ^d$$  \hspace{1cm} (2)

where $a$, $b$, $c$, and $d$ are empirical parameters.
Using Equation (2) and a gate length of $\Delta r$, $\text{PIA}_i$ in gate $i$ can be obtained by

$$\text{PIA}_i = c \left( Z_i + \sum_{j=0}^{i-1} cZ_j^d \right)^{d/2} \cdot 2\Delta r$$

(3)

Reflectivity $Z_i$ (as dBZ) in any range gate $i$ would then be corrected to $Z_{\text{corr},i}$ by adding the corresponding $\text{PIA}_i$ (dB):

$$Z_{\text{corr},i} = Z_i + \text{PIA}_i$$

(4)

Parameters $c$ and $d$ depend on the unknown rainfall properties listed above. The uncertainty of these parameters can introduce substantial errors in the estimation of $A$ and thus cause instability of gate-by-gate correction. Other sources of error are e.g. the presence of non-rain scatterers (such as clutter or hail) or radar miscalibration.

As pointed out before, errors in the estimation of $A$ will accumulate and grow exponentially over the propagation path. Hence, there is a consensus that the original gate-by-gate correction is unstable and not helpful for unsupervised application.

In this study, we evaluated four processing variants which differ with regard to the underlying attenuation correction approach, in particular in how they constrain estimates of $\text{PIA}$ in order to avoid instability. The variants are the following:

2.2.2.1. Raw. No attenuation correction is applied. Instead, reflectivity $Z$ is directly converted to rainfall intensity $R$ (see section 2.2.3).

2.2.2.2. Harrison. Harrison et al. (2000) suggested applying a conventional gate-by-gate correction (using an $A(R)$ relation according to Equation (1) and capping the correction of rainfall intensity at a factor of two. This corresponds to constraining $\text{PIA}$ between 4 and 5 dB, depending on parameters $a$ and $b$ of the $Z(R)$ relationship (4.8 dB if we assume $a = 200$ and $b = 1.6$, see Section 2.2.3). Accordingly, we used 4.8 dB to cap the computed $\text{PIA}$. To be more consistent with the other variants, we computed $\text{PIA}$ using an $A(Z)$ relation (with $c = 4.57 \cdot 10^{-5}$ and $d = 0.731$) instead of the original $A(R)$ relationship suggested by Harrison et al. (2000). However, in our view, the prime feature of this approach is not the computation of $A$, but the way of constraining $\text{PIA}$.

2.2.2.3. Kraemer. Based on attenuation reference measurements with a microwave link, Kraemer and Verworn (2008) identified optimal combinations of parameters $c$ and $d$ of the $A(Z)$ relation (Equation (2)). They also found that, within one event, the optimal $c-d$ combination was not unique and could vary rapidly between scans. However, they established that attenuation can be successfully retrieved if the exponent $d$ was fixed while only the linear coefficient $c$ was varied. For estimating $c$ in the absence of any attenuation reference, Kraemer and Verworn (2008) suggested an iterative search procedure under the (admittedly strong) assumption that $c$ is optimal if it does not cause instability. This is realized by starting the iteration with a relatively high initial guess of the linear coefficient $c$ which we would expect to cause instability for convective situations. For C-band frequency, Kraemer recommends to fix the exponent to $d = 0.7$ and to set the initial value of the linear coefficient to $c = 1.67 \cdot 10^{-8}$. The linear coefficient is then successively reduced for contiguous beam sectors until stability is achieved. As a criterion to detect instability, Kraemer (2008) arbitrarily defined the case in which the value of attenuation-corrected reflectivity in any gate exceeded a maximum of $Z_{\text{corr},\text{max}} = 59$ dBZ. This threshold is somewhat supported by numerical experiments conducted by Islam (2008) who found attenuation correction schemes to become unstable in case true reflectivity exceeded 60 dB. If there are just a few adjacent unstable beams, the $\text{PIA}$ for the last
gate is interpolated between two stable beams as reference PIA. As a result, the algorithm derives attenuation coefficients for contiguous beam sectors in every scan.

2.2.2.4. MKRAEMER (modified Kraemer approach). Obviously, the validity of the procedure depends on its ability to detect instability. From an operational perspective, the arbitrary choice of the threshold \( Z_{\text{corr},\text{max}} \) is legitimate. However, we found that in situations of extreme rainfall intensities, PIA estimates according to KRAEMER might exceed values of 45 dB (see Section 3). This is possible in situations with an almost entire loss of signal. Considering the signal-to-noise ratio in the corresponding beam segments, though, attempts to recover the actual rain rate by multiplicative procedures is unreasonable.

Correspondingly, we enhanced the KRAEMER scheme by introducing an upper limit \( \text{PIA}_{\text{max}} = 20 \text{ dB} \) as an additional criterion to define instability. As a consequence, the attenuation correction along a beam is considered as unstable if \( \text{PIA} \) exceeds values of 20 dB or if \( Z_{\text{corr}} \) exceeds a threshold of 59 dBZ. This is in agreement with PIA observations between radar and mountain reference targets at a distance of 120 km (Bouilloud et al. 2009), although Bouilloud et al. (2009) and Delrieu et al. (2000) recommend to limit the maximum PIA to 10 dB due to instabilities in the gate-by-gate approach even with known rainfall properties. However, with the proposed ‘double constrain’, we expect that corrected reflectivity will not diverge radically and PIA is kept in plausible but not conservative limits.

This means a significant source of instability is removed at the cost of losing the ability to correct for extreme losses of the radar signal. Using the Marshall and Palmer \( Z(R) \) relationship, a PIA of 20 dB would correspond to multiplicative factors of 17.8 on the rain rate. In contrast to the approach of Harrison et al. (2000), this implies that we do not simply truncate \( \text{PIA} \) values higher than \( \text{PIA}_{\text{max}} \), but instead reduce the linear coefficient of the attenuation-reflectivity relationship iteratively until they fall below \( \text{PIA}_{\text{max}} \) in the same way as mentioned for the reflectivity constraint. This way, we achieve consistent \( \text{PIA} \) values along the entire radar beam. However, that means in the rare situations where actual PIA of more than 20 dB occur this method is not able to retrieve the potentially unattenuated signal strength anymore. The rain intensities are then significantly underestimated. E.g. spikes of total signal attenuation will remain in the corrected data.

2.2.3. Relationship between rain rate and radar reflectivity

The rainfall intensity \( R \text{ (mm h}^{-1} \text{)} \) can be related to the horizontal reflectivity \( Z \text{ (mm}^6 \text{ m}^{-3} \text{)} \) in the form of a power law:

\[
Z = aR^b
\]  

(5)

Due to a lack of additional information on the type of hydrometeors and the drop size distribution, we applied the conventional \( Z(R) \) relationship with the empirical parameters \( a = 200 \) and \( b = 1.6 \) as found by Marshall and Palmer (1948) in order to derive the rain rates.

2.3. Verification

For the long-term verification, we used hourly precipitation observations from a set of 190 rain gauges within the coverage of Feldberg radar. Using hourly accumulation intervals for verification is, first, a trade-off between enhancing the representativeness of point measurements at the ground (see e.g. Kitchen & Blackall 1992) and focussing on the time scale of interest (which might be below an hour). Second, the number of gauges recording at hourly resolution is simply much higher, implying a better basis for verification. Still, it should be kept in mind that attenuation — same as rainfall intensity — can vary substantially within minutes.
For verification, we use the root mean square error (RMSE, Equation (6)) to quantify the overall estimation error and the percent bias (pBias, Equation (7)) in order to quantify the systematic estimation error:

\[
\text{RMSE} = \left[ \frac{1}{n} \sum_{i=1}^{n} (r_i - g_i)^2 \right]^{0.5}
\]

\[
\text{pBias} = \frac{\sum_{i=1}^{n} (r_i - g_i)}{\sum_{i=1}^{n} g_i}
\]

The radar-based rainfall estimate \( r_i \) is the value of the radar bin which is situated closest to the corresponding gauge observation \( g_i \) out of \( n \) gauges.

3. Results and discussion

3.1. Case study

Before presenting the long-term verification results, we would like to exemplify the behaviour of different attenuation correction procedures for a selected beam and for a selected event. Figure 2 shows the rainfall situation on 2 June 2008, 16:55 UTC (universal time, coordinated), by means of a plan position indicator (PPI) of observed reflectivity. The situation marks the passage of a meso-scale convective system that brought heavy convective precipitation over parts of South-West Germany, including a devastating flash flood in the river Starzel (see Ruiz-Villanueva et al. 2012). Rainfall

Figure 2. PPI of reflectivity as observed by DWD radar Feldberg on 2 June 2008 at 16:55 UTC. The white line marks the beam at an azimuth of 54°. Please refer to Figure 3 in which range profiles of the beams at 53°, 54°, and 55° are presented. Note that this PPI represents the raw radar observation without any additional clutter removal.
activity is particularly pronounced in the north-eastern sector of the radar, including an alignment of precipitation cells that might imply severe signal attenuation. This is substantiated in Figure 3 which shows range profiles of reflectivity and PIA around three beams marked by the white line in Figure 2. In addition to the three attenuation correction procedures outlined in Section 2.3 (HARRISON, KRAEMER, and MKRAEMER), Figure 3 also exemplifies the behaviour of the ‘conventional’ (unconstrained) Hitschfeld—Bordan algorithm.

As expected, the profiles of retrieved PIA along the beams suggest strong attenuation. Interestingly, the algorithm according to Hitschfeld and Bordan (1954) behaves quite stable for two of the three selected beams. However, instability is demonstrated for the beam at an azimuth angle of 53°. As compared to the Hitschfeld and Bordan example, the method according to HARRISON uses a smaller coefficient of in the relation. This is why the capping threshold of for (see Section 2.3) is reached at more distant ranges as compared to Hitschfeld and Bordan: while at 55° is not capped at all, at 53° is capped at about 56 km, and at 54° at about 78 km. For the KRAEMER approach, at 54° and 55° is even higher than PIA as computed according to Hitschfeld and Bordan. This is because the iterative search procedure of the KRAEMER approach starts from very high initial values of and (see Equation (2)) and the iteration is stopped as soon as the constraint criterion is met. This way, PIA values of up to 30 dB are obtained. The MKRAEMER approach considers another constraint in the iterative search which restricts PIA to values below 20 dB. As the result all three profiles of PIA stay below 20 dB. Compared to the results according to Hitschfeld and Bordan, PIA along 53° is much lower (i.e. stable), PIA along 54° is almost the same, and PIA along 55° is higher than for Hitschfeld and Bordan (because MKRAEMER also starts out from high values of and ). The lowermost panel of Figure 3 exemplarily shows for the beam at 54° the hourly rain accumulations along the beam as a result of the uncorrected radar data and the three correction approaches. Since the accumulation is based on 12 consecutive scans, its comparability to the panels above is limited. This way, however, the radar-based rain accumulation is comparable to the rain accumulations at gauges along the propagation path. The radar-based rain accumulations corrected with the KRAEMER and the MKRAEMER approach are in very good agreement with the rain gauge data at village Metzingen-Neuhausen (122 km). At both rain gauges in Rottweil (58 km), the raw radar data as well as the corrected radar data seem to underestimate the rain amount. This divergence may be a result of the small-scale heterogeneity of convective rain events. That would explain the difference of more than 25% even between both rain gauges that are only 281m away from each other.

The effects of attenuation correction also become apparent when looking at the entire event on June 2nd. The main event mainly took place in the North-Eastern radar sector and lasted for about seven hours. Figure 4 shows the accumulated rainfall depths between 13:00 and 20:00 UTC that result from the different processing variants. Figure 5 shows the scatter plots obtained from the comparison of radar-based rainfall estimates to rain gauge observations. As compared to the RAW estimate, all three attenuation correction procedures improve the rainfall estimates. Rainfall obtained from the RAW variant underestimates the accumulated rainfall (by 32 percent). So does — to a lesser extent — the estimate according to HARRISON (by 22 percent). KRAEMER and MKRAEMER reduce the bias and both lead to a substantial reduction of the RMSE (to 5.4 and 5.5 mm h⁻¹). Both rainfall maps and the scatter reveal only minor differences between KRAEMER and MKRAEMER. Still, with the RMSE being more or less equivalent, MKRAEMER appears to perform slightly better with a pBias of only 7 percent (as compared to 13 percent with KRAEMER) — at least for this specific case study.

To demonstrate the intermittent behaviour of attenuation on radar rainfall, Figure 6 shows the temporal dynamics of hourly rain depths at a rain gauge near Hayingen between 16:00 and 23:00 UTC. From 16:00 till 18:00, intensive precipitation between the radar station and the rain gauge attenuates the signal remarkably and only the attenuation corrected (MKRAEMER) radar estimates are able to match the rain gauge observation. From 18:00 after the intense storm cells had vanished, the corrected radar-based precipitation estimations conform to the uncorrected estimations.

However, Figure 5(c) and 5(d) also demonstrate cases of substantial overestimation of rainfall at a number of rain gauges. A striking example is highlighted by the points marked by the circles in
Figure 3. Range profiles of reflectivity and PIA on 2 June 2008 at 16:55 UTC for the three beams from 53°–55° of radar Feldberg (position indicated by the white line in Figure 2). The uppermost panel shows observed reflectivity along the three beams; the four lower panels show PIA according to different methods: in addition to HARRISON, KRAEMER, and MKRAEMER, we also exemplify the behaviour of the unconstrained gate-by-gate algorithm according to Hitschfeld and Bordan (1954), applying $A(Z) = 8 \times 10^{-13} Z^{0.73}$. The lowermost panel shows the conversion of the beam reflectivity at 54° to rain amounts between 16:30 and 17:30 UTC. The raw reflectivity and the three correction methods are compared to rain gauges, located along the beam.
Figure 5(d). However, it was not possible to identify unambiguous reasons for this behaviour. Most likely, the overestimation is a random effect that was caused by the fact that the corresponding radar bins are located at outmost range of the radar (128 km) so that uncertainties of the procedure could maximally accumulate along the propagation path. Effects of hail, though, could be ruled out since none of the radar scans included in the event accumulation around these rain gauges showed reflectivity values that would be expected for hail. In addition, the strong spatial heterogeneity of the spatial rainfall field in that situation also gives rise to the expectation that substantial deviations (e.g., wind drift effects) will occur when comparing the volume integrated measurements to the point observations of the rain gauges.

### 3.2. Long-term verification

The objective of this study is to investigate the behaviour of different attenuation correction procedures over a wide range of conditions, in order to evaluate both effectiveness and robustness. Therefore, we applied the procedures as outlined in Sections 2.2 and 2.3 over a contiguous period of six years from 2007 until 2013, and compared the radar-based precipitation estimates to the corresponding rain gauge observations at an accumulation interval of one hour.

Figure 7 shows the estimation error of the four different processing variants. The upper panel shows the RMSE of the uncorrected radar-based rainfall estimate (RAW). The centre panel indicates
Figure 5. Scatter plots and quality measures for the four processing variants, obtained from the comparison between radar-based rainfall estimates and rain gauge observations accumulated from 13:00 to 20:00 UTC, 2 June 2008: (a) RAW, (b) HARRISON, (c) KRAEMER, and (d) MODIFIED KRAEMER.

Figure 6. Time series of hourly rain depths of rain gauge observations, uncorrected, and corrected (MODIFIED KRAEMER) radar data on 2 June between 16:00 and 23:00 UTC at rain gauge near village Hayingen.
the reduction of RMSE as obtained by attenuation correction. According to Section 2.3, the RMSE was computed from the pairs of hourly rain gauge observations and radar-based rainfall estimates (‘gauge-radar’ pairs). The figure is organized in a way that it illustrates the effects of attenuation correction depending on rainfall intensity. For that purpose, we successively removed those hourly time steps from the computation of the RMSE in which none of the rain gauges exceeded a minimum threshold. This threshold is represented by the x-axis and was increased from 0 to 50 mm by 1 mm increments. The bottom panel illustrates the number of remaining hourly time steps after filtering. This way, we start with the overall performance of the correction procedures and successively focus on situations with the occurrence of heavy rainfall. In a reduced form, Table 2 also summarizes these verification results with only three rainfall thresholds, including the percent Bias as a verification measure.

First of all, we can see that each of the considered attenuation correction procedures reduces the estimation error as compared to the estimate from uncorrected reflectivity (RAW) — both in terms of percent bias (see Table 2) and RMSE (see Table 2 and Figure 7). Furthermore, the HARRISON approach caps PIA at a fixed threshold, hence cannot account for the full extent of attenuation in situations of heavy rainfall. Accordingly, the reduction of the RMSE obtained from HARRISON is limited. In contrast, KRAEMER and mKRAEMER perform particularly well in cases of heavy precipitation. The difference between KRAEMER and mKRAEMER is admittedly small. KRAEMER performs particularly well for high intensities, while it performs a little worse than HARRISON at thresholds below 4 mm. In contrast, mKRAEMER appears to reduce the RMSE coherently over the full range of rainfall intensities,
i.e. it performs equivalent or better than both HARRISON and KRAEMER for all thresholds. This implies that the trade-off between stability and correction of attenuation is actually quite small: the additional constraint added by MKRAEMER is not at the cost of capturing severe attenuation, yet it leads to more robust results at low and moderate intensities.

### 4. Summary and conclusions

Forward gate-by-gate attenuation correction has been repeatedly and legitimately criticized for inherent instability and the resulting errors in precipitation estimation. While radar polarimetry introduced more robust alternatives to deal with PIA, the need to address attenuation for single-polarized radar observations remains effective: single-polarized radars are still widely spread in operational services, and observations archived over the past 10–20 years represent valuable assets for reanalyses. In this study, we evaluated the potential of three forward attenuation correction approaches which do not require any additional reference measurements. The question was whether the investigated algorithms could reduce attenuation-induced estimation errors without compromising operational applicability. To answer this question, different algorithms have been benchmarked over a contiguous period of six years. While all procedures led to a reduction of the RMSE over the full range of rainfall intensities, we could show that simply capping PIA (as suggested by Harrison et al. 2000) does not allow for tapping the full potential of gate-by-gate algorithms. Instead, the iterative procedure suggested by Kraemer (2008) allowed for an unambiguous reduction of estimation errors over a wide range of rainfall situations from medium to high intensity. By supplementing Kraemer’s approach with another constraint on maximum PIA, we could achieve an additional improvement of rainfall estimation. While the general behaviour of the different algorithms was following expectations, it was surprising to see the excellent performance of the Kraemer approach under heavy rainfall conditions.

The procedures investigated in this study are transparently implemented and freely available in the Open Source Software wradlib. This way, they can easily be tested for other radars or other environments. On [http://wradlib.org/wradlib-docs/latest/tutorial_attenuation.html](http://wradlib.org/wradlib-docs/latest/tutorial_attenuation.html), we present a short tutorial on how to apply the different correction procedures. wradlib allows for a flexible combination of different constraints (namely constraints for maximum corrected reflectivity and maximum PIA) and their corresponding threshold values. wradlib also allows to set the ranges and increments which are used to iterate over the parameters of the \( A(Z) \) relationship. This way, users can tune their own data processing chain to an acceptable trade-off between attenuation correction and robustness, and might find further potential for the improvement of estimation quality. The findings should also be scrutinized by long-term verification experiments with other radars.

The constrained forward gate-by-gate correction procedures benchmarked in this study are easy to implement and they do not require any additional source of information. Despite all the criticism of cumulative gate-by-gate approaches, we could show that, at least for the Feldberg radar, the trade-off between attenuation correction and instability is surprisingly low for both the KRAEMER and the modified Kraemer (MKRAEMER) algorithm. Based on this finding, we recommend to prefer this kind of iterative correction procedures for applications in which heavy convective rainfall plays a substantial role, e.g. in flash flood forecasting or in the emerging field of radar-based extreme value statistics.

| Rainfall threshold | RAW   | HARRISON | KRAEMER | MKRAEMER |
|--------------------|-------|----------|---------|----------|
| RMSE (mm)          |       |          |         |          |
| >1 mm              | 0.77  | 0.76     | 0.77    | 0.76     |
| >5 mm              | 1.34  | 1.31     | 1.31    | 1.29     |
| >10 mm             | 1.85  | 1.79     | 1.75    | 1.72     |
| pBias (%)          |       |          |         |          |
| >1 mm              | −51.6 | −48.9    | −43.4   | −43.4    |
| >5 mm              | −53.8 | −49.8    | −40.3   | −41.7    |
| >10 mm             | −52.4 | −48.1    | −35.3   | −36.3    |
Acknowledgments

The radar data were provided by the German Weather Service (DWD), and rain gauge data by the Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW). In this context, we would like to thank Angela Sieber for her substantial support.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the German Federal Ministry for Education and Research (BMBF) under grant of the PROGRESS project (http://www.earth-in-progress.de).

Notes on contributors

Stephan Jacobi is a postgraduate of flash flood forecasting at the University of Potsdam. His research focuses on radar-based quantitative precipitation estimations. He was involved in the establishment of the Open Source Software library for radar data processing: wradlib. He examines different workflow scenarios for real-time flash flood nowcasting, their verification and uncertainties.

Maik Heistermann is research associate at the University of Potsdam, Institute of Earth and Environmental Sciences. He is one of the lead developers of the Open Source Software library wradlib. His research focuses on radar hydrology in tropical and temperate environments, and the role of Open Source Software to make progress sustainable, transparent and reproducible.

References

Bringi VN, Chandrasekar V, Balakrishnan N, Zrnić DS. 1990. An examination of propagation effects in rainfall on radar measurements at microwave frequencies. J Atmospheric Oceanic Technol. 7:829–840.

Bouilloud L, Delrieu G, Boudevillain B, Borga M, Zanon F. 2009. Radar rainfall estimation for the post-event analysis of a Slovenian flash-flood case: application of the Mountain Reference Technique at C-band frequency. Hydrol Earth Syst Sci. 13:1349–1360.

Chandrasekar V, Lim S. 2008. Retrieval of reflectivity in a networked radar environment. J Atmospheric Oceanic Technol. 25:1755–1767.

Delrieu G, Caoudal S, Creutin JD. 1997. Feasibility of using mountain return for the correction of ground-based C-band weather radar data. J Atmospheric Oceanic Technol. 14:368–385.

Delrieu G, Andrieu H, Creutin JD. 2000. Quantification of path-integrated attenuation for X- and C-band weather radar systems operating in mediterranean heavy rainfall. J Appl Meteorol. 39:840–850.

Gabella M, Notarpeitro R. 2002. Ground clutter characterization and elimination in mountainous terrain. In: Proceedings of ERAD; 2002 Nov 18–22; Delft (Netherlands); p. 305–311.

Gunn KLS, East TWR. 1954. The microwave properties of precipitation particles. Q J Roy Meteorol Soc. 80:522–545.

Harrison DL, Driscoll SJ, Kitchen M. 2000. Improving precipitation estimates from weather radar using quality control and correction techniques. Meteorol Appl. 6:135–144.

Heistermann M, Jacobi S, Pfaff T. 2013. Technical note: an open source library for processing weather radar data (wradlib). Hydrol Earth Syst Sci. 17:863–871.

Hendrantoro G, Zawadzki I. 2003. Derivation of parameters of Y-Z power-law relation from raindrop size distribution measurements and its application in the calculation of rain attenuation from radar reflectivity factor measurements. IEEE Trans Antennas Propag. 51:12–22.

Hildebrand PH. 1978. Iterative correction for attenuation of 5 cm radar in rain. J Appl Meteorol. 17:508–514.

Hitschfeld W, Bordan J. 1954. Errors inherent in the radar measurement of rainfall at attenuating wavelengths. J Meteorol. 11:58–67.
Islam M. 2008. Stability limit on numerical attenuation correction algorithm for single polarized radars. J Hydrol Eng. 13:1197–1201.

Kitchen M, Blackall RM. 1992. Representativeness errors in comparisons between radar and gauge measurements of rainfall. J Hydrol. 134:13–33.

Kraemer S. 2008. Quantitative radar data processing for rainfall forecasting and urban drainage [dissertation]. Hannover: Gottfried Wilhelm Leibniz University.

Kraemer S, Verworn HR. 2008. Improved C-band radar data processing for real time control of urban drainage systems. In: Proceedings of the 11th International Conference on Urban Drainage; 2008 Aug 31 – Sep 5; Edinburgh (UK): Edinburgh International Conference Centre.

Marshall JS, Palmer WM. 1948. The distribution of raindrops with size. J Meteorol. 5:165–166.

Olsen RL, Rogers DV, Hodge DB. 1978. The aRᵇ relation in the calculation of rain attenuation. IEEE Trans Antennas Propag. 26:318–329.

Overeem A, Buishand TA, Holleman I, Uijlenhoet R. 2010. Extreme value modeling of areal rainfall from weather radar. Water Resour Res. 46:W09514.

Rahimi AR, Holt AR, Upton GJG, Krämer S, Redder A, Verworn HR. 2006. Attenuation calibration of an X-band weather radar using a microwave link. J Atmospheric Oceanic Technol. 23:395–405.

Ruiz-Villanueva V, Borga M, Zoccatelli D, Marchi L, Gaume E, Ehret U. 2012. Extreme flood response to short-duration convective rainfall in South-West Germany. Hydrol Earth Syst Sci. 16:1543–1559.

Ryzhkov A, Zrinić DS. 1996. Assessment of rainfall measurement that uses specific differential phase. J Appl Meteorol. 35:2080–2090.

Testud JE, Le Bouar E, Obligis E, Ali-Mehenni M. 2000. The rain profiling algorithm applied to polarimetric weather radar. J Atmospheric Oceanic Technol. 17:332–356.

Troemel S, Ziegert M, Ryzhkov AV, Chwala C, Simmer C. 2014. Using microwave Backhaul links to optimize the performance of algorithms for rainfall estimation and attenuation correction. J Atmospheric Oceanic Technol. 31:1748–1760.

Vulpiani G, Tabary P, Chatellet JPD, Marzano FS. 2008. Comparison of advanced radar polarimetric techniques for operational attenuation correction at C band. J Atmospheric Oceanic Technol. 25:1118–1135.