A Simple Method for Attenuation Correction in Local X-Band Radar Measurements Using C-Band Radar Data

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(Manuscript received 4 May 2015, in final form 12 July 2016)

ABSTRACT

This paper presents a novel, simple method to correct reflectivity measurements of weather radars that operate in attenuation-influenced frequency bands using observations from less attenuated radar systems. In recent years radar systems operating in the X-band frequency range have been developed to provide precipitation fields for areas of special interest in high temporal (≤1 min) and spatial (≤250 m) resolution in complement to nationwide radar networks. However, X-band radars are highly influenced by attenuation. C- and S-band radars typically have coarser resolution (250 m–1 km and 5 min) but are less affected by attenuation.

Correcting for attenuation effects in simple (non-Doppler) single-polarized X-band radars remains challenging and is often dependent on restriction parameters, for example, those derived from mountain returns. Therefore, these algorithms are applicable only in limited areas. The method proposed here uses measurements from C-band radars and hence can be applied in all regions covered by nationwide C- (or S-) band radar networks. First, a single scan of X-band radar measurements is used exemplary to identify advantages and disadvantages of the novel algorithm compared to a standard single radar algorithm. The performance of the correction algorithms in different types of precipitation is examined in nine case studies. The proposed method provides very promising results for each type of precipitation. Additionally, it is evaluated in a 5-month comparison with Micro Rain Radar (MRR) observations. The bias between uncorrected X-band radar and MRR data is nearly eliminated by the attenuation correction algorithm, and the RMSE is reduced by 20% while the correlation of ~0.9 between both systems remains nearly constant.

1. Introduction

In recent years numerous extreme weather events in the form of heavy and long-lasting rainfall caused serious damage, especially in urban environments. To anticipate and forecast these events, detailed information on the precipitation field is required because of the high temporal and spatial variability of precipitation. Ochoa-Rodriguez et al. (2015) investigated the influence of rainfall input resolution on hydrodynamic simulations in urban areas and suggest a spatial resolution of ~100 m and a temporal resolution below 5 min for drainage areas smaller than 1 ha. Rafieeininasab et al. (2015) also pointed out the importance of high temporal resolution in precipitation data for flash flood prediction in urban areas.

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DOI: 10.1175/JTECH-D-15-0091.1

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Currently, observations from ground-based in situ precipitation observations (e.g., rain gauge or disdrometer networks) or products from conventional radar systems from nationwide networks based on reflectivity measurements at S- or C-band wavelengths are used as input for forecasting and nowcasting models (Moreno et al. 2013; Wang et al. 2012; Liguori and Rico-Ramirez 2012; Germann et al. 2009). These radar networks derive precipitation estimates with a spatial resolution of typically 250 m–1 km and a temporal resolution on the order of 5 min. In situ networks provide data with even coarser resolution. The C-band radar network of the German Meteorological Service [Deutscher Wetterdienst (DWD)] has been recently upgraded to polarimetric C-band systems. Also, the averaging of the 125-m range bins within the signal processor has been changed to provide precipitation fields with high spatial resolution (~250 m), but the systems still lack high temporal resolution. To meet present and future demands of resolution, recent studies support observations at X-band frequencies as an alternative or as an addition to the S and C bands (Lengfeld et al. 2014; Trabal et al. 2013). Besides higher resolution, radars operating at higher frequencies have the advantage of lower costs because of smaller antenna size compared to longwave radars.

These high-resolution weather radars can fill gaps in existing nationwide radar networks or provide precipitation estimates with higher temporal and spatial resolution in areas of special interest, for example, urban areas (Chen and Chandrasekar 2012; van de Beek et al. 2010), near airports (Turso et al. 2009), in mountainous regions (Beck and Bousquet 2013; P.C. et al. 2013; Figueras i Ventura and Tabary 2013), or in flood prone regions (Matrosov et al. 2013). The downside of low-cost high-resolution systems is significant attenuation due to liquid water, especially in the X- and K-band frequency ranges (e.g., Gunn and East 1954; Atlas and Ulbrich 1977; to mention only the earliest studies). The magnitude of attenuation is generally inversely proportional to the wavelength. Thus, reflectivity measurements from X-band radars are much more affected by attenuation than those from S- and C-band radars. To obtain valuable estimates of the rainfall field from reflectivity observations of these high-resolution systems, precise estimation of attenuation is crucial. One way to correct for attenuation is to use dual-polarized X-band radars. These systems allow for determination of attenuation using specific differential phase, for example, Park et al. (2005). Therefore, the quality of their reflectivity measurements and, consequently, precipitation estimates are comparable to C- and S-band performance. Nevertheless, dual-polarized systems are more expensive than the simple single-polarized radars that are investigated in this study.

To overcome the drawback of attenuation in reflectivity measurements of single-polarized radars, Testud and Amayenc (1989) and Srivastava and Tian (1996) introduced concepts of overlapping networks of high-resolution weather radars (HRWR) that allow for determination and correction of attenuation. For single-polarized X-band radars, correction algorithms make use of a fixed target signal to scale attenuation (e.g., mountain returns; Delrieu et al. 1997). In cases where no fixed targets are available, stable and valid attenuation correction for single-polarized X-band radars remains challenging.

This paper presents a new method to correct for attenuation in X-band radar measurements using observations of less attenuated large-scale C- (or S-) band radars and is applicable in every region covered by one of those systems. It is organized as follows: Section 2 presents the radar systems used in this study. Technical details of the C- and X-band radar networks are given. The investigated methods for estimating attenuation in X-band radar measurements based on observations from X- and C-band radars are described in section 3. Section 4 gives a comprehensive evaluation of the performance of the proposed method in comparison with a common attenuation correction method. The algorithms are applied exemplary to a single scan of X-band radar measurements to point out the advantages and disadvantages of each method. Nine case studies and a long-term comparison with reflectivity measurements from Micro Rain Radars (MRRs) assess the quality of the proposed method in different types of precipitation. In section 5 conclusions are drawn and an outlook on future work is given.

2. Radar network

A network of four local area weather radars (LAWRs) has been installed north of Hamburg, Germany (Fig. 1), within the project Precipitation and Attenuation Estimates from a High-Resolution Weather Radar Network (PATTERN). A fifth LAWIR is installed on the rooftop of the Meteorological Institute, covering the whole urban area of the city of Hamburg. The LAWRs are modified ship navigation radars (GEM Elettronica scanner SU70-25E) that cannot observe Doppler shift nor do they perform polarimetric measurements. They perform horizontal scans with a fixed elevation angle of ~3° every 30 s with a range resolution of 60 m and an angular sampling resolution of 1° in azimuth direction. Each LAWIR has a maximum range of 20 km in radius around the site. Neighboring radars are between 11 and 16 km apart. Therefore, the network covers a region of around 60 km × 80 km. Technical
details can be found in Table 1, and a detailed description of the network is given in Lengfeld et al. (2014).

For calibration and evaluation purposes, a number of precipitation-observing instruments are set up within the area of the network. MRRs are installed at each radar site and at three reference stations [Kellinghusen (OST), Oelixdorf (MST), and Itzehoe (WST)] with rain gauges. MRRs are vertically profiling K-band radars that measure Doppler spectra of hydrometeors at 31 height levels with a height resolution of 35 m to retrieve the drop size distribution (DSD). They use single-particle backscattering cross sections that are calculated with Mie theory using the algorithm of Morrison and Cross (1974). Radar reflectivity factor $Z_{\text{MRR}}$ is derived from MRR DSDs using Rayleigh approximation (Peters et al. 2005) and therefore is independent of the wavelength. For attenuation correction in MRR measurements, the spectral scheme proposed by Peters et al. (2010) is applied. These reflectivity measurements serve as reference to investigate the performance of the proposed C-band based attenuation correction. Using profiling MRRs instead of rain gauges allows for comparing reflectivity measurements in the observing height of the radars and therefore in nearly the same volume instead of comparing computed precipitation estimates with ground-based measurements.

The X-band radars are calibrated with MRR observations at different locations in the corresponding volumes as described in Lengfeld et al. (2014). The calibration coefficients for each X-band radar are calculated by averaging the calibration coefficients determined for each X-band radar–MRR combination. Beforehand, MRRs are calibrated near the ground using comparisons to rain gauges (also described in Lengfeld et al. 2014).

The PATTERN region is covered by a C-band radar operated by the DWD. The C-band radar is located in Hamburg and observes a 128-km radius around the city. It measures reflectivity with a temporal resolution of 5 min and a spatial resolution of 1 km. The C-band radar transmitter is calibrated by the DWD using a calibrated power meter. For calibrating the receiver, calibrated signal generators are used. Losses due to radome and cables are estimated according to specifications by the manufacturer. Attenuation in C-band radar is corrected using the method proposed by Hitschfeld and Bordan (1954). A comparison with MRR measurements before and after attenuation correction (not shown here) demonstrated that bias ($\approx 0.77$ dB) and variability (4.57 dB) remain nearly constant. Therefore, it is legitimate to assume only minimal influence of attenuation and to use C-band radar observations for attenuation correction in X-band radar measurements. More technical specifications are listed in Table 1.

### 3. Methods

The X-band frequency range is highly influenced by attenuation. Correction algorithms are essential in order to derive reliable reflectivity observations and therefore precipitation estimates. Hitschfeld and Bordan (1954) developed a straightforward method for attenuation correction. The downside of the Hitschfeld and Bordan (HB) method is its instability and sensitivity to radar calibration errors.

The intrinsic reflectivity factor $Z(r)$ can be calculated with the measured apparent reflectivity factor $Z_{\text{MRR}}(r)$, a
constant radar calibration error $\varepsilon$ (assumed to be 1 in this study), and the multiplicative path-integrated attenuation factor $A(r)$ at a range gate $r$ that is dependent on the path-integrated attenuation (PIA) as follows:

$$Z_{am}(r) = \varepsilon Z(r) A(r),$$

where $Z(r)$ and $Z_{am}(r)$ are in mm$^6$ m$^{-3}$. PIA and therefore the PIA factor at a range $r$ are dependent on the integral over specific attenuation coefficient $k$ (dB km$^{-1}$) and is given as

$$A(r) = 0.46 \int_0^r k(s) \, ds,$$

where $k$ varies with the drop size distribution and the temperature of the raindrops, as well as with the operating wavelength.

Marzoug and Amayenc (1994) demonstrated that (1) can also be written as

$$d[A(r)^{1/\beta}] = \frac{0.46}{\beta} \left[ \frac{Z_{am}(r)}{\alpha \varepsilon} \right]^{1/\beta} dr,$$

using the power-law relation between $Z_{am}$ (mm$^6$ m$^{-3}$) and specific attenuation coefficient $k$

$$Z = \alpha k^\beta.$$

Coefficients $\alpha$ and $\beta$ are dependent on the operating frequency of the radar. In this study $\alpha = 132250$ and $\beta = 1.2$ for X-band frequency range are used as derived by Delrieu et al. (1997) for $Z$ (mm$^6$ m$^{-3}$) and $k$ (dB km$^{-1}$). Integrating (3) from the radar (range $r_0$) to a range $r$ leads to

$$A(r) = \left[ A(r_0)^{1/\beta} - \frac{0.23}{\beta \alpha^{1/\beta}} \text{PIA}(r) \right]^{\beta},$$

with

$$\text{PIA}(r) = 2 \int_0^r \left[ \frac{Z_{am}(s)}{\alpha} \right]^{1/\beta} ds.$$

being the two-way PIA away from and back to the radar. The term to be integrated is the specific attenuation as calculated from (4) (dB km$^{-1}$). Integrating $k$ over distances $ds$ (km) results in the path-integrated attenuation (dB).

In this study the focus lies on attenuation effects due to liquid water. Therefore, all other sources of error, such as the blind range attenuation and radar mis-calibration, are assumed to be negligible and $A(r_0)$ and $\varepsilon$ are set to 1, which yields the following simplified version of (5) defining the PIA factor $A$ for a certain $r$:

$$A(r) = \left[ 1 - \frac{0.23}{\beta} \text{PIA}(r) \right]^{\beta}.$$

In a first attempt to correct reflectivity data obtained by X-band radars within the PATTERN network, the HB method is applied for single-polarized radars. The determination of PIA and therefore $A(r)$ work only along a path with undisturbed measurements. Data gaps occur along radar radials due to disturbances in the radar image caused by nonmeteorological echoes, for example, external emitters and obstacles, such as trees or houses, which need to be removed. To apply the HB attenuation correction, these gaps need to be filled. In overlapping areas within a network, the advantage of more information from different radars can be used to fill data gaps. For single-polarized radars spatial interpolation is necessary. Reflectivity values of the surrounding range bins will be averaged to estimate the reflectivity in the data gap. This procedure allows for calculation of PIA along radar beams, but it smoothes out the small-scale structure of precipitation and therefore deprives the X-band radar data of one of its advantages.

Another well-known problem of the HB attenuation correction algorithm is its instability in case of high reflectivities and strong attenuation. To avoid this instability, Delrieu et al. (1997) proposed a method that makes use of the reflectivity signal of a mountain as a delimiter for maximum possible attenuation. The ratio of apparent reflectivity of the mountain during rainy and dry weather conditions is used as a constraint for the total PIA. Although Delrieu et al. (1997) achieved good results with their correction algorithm, it is not feasible within the PATTERN network area because it is located in a rather flat region.

To correct even highly attenuated measurements, a novel method is proposed that combines advantages of X- and C-band systems. Reflectivity measurements in the C-band frequency range are less affected by attenuation due to liquid water than in the X-band frequency range. The C-band radar, which covers the X-band radar network area, observes reflectivity in coarser temporal and spatial resolution than the X-band radars. Therefore, the C-band reflectivity fields need to be interpolated in time and refined in space to match the resolution of X-band-derived fields. For the temporal interpolation, the C-band radar observations prior and posterior to the X-band radar observation are averaged weighted with the temporal distance to the X-band radar observation. Because of the use of future data, this
method is applicable only for postprocessing. To use it for real-time applications, a tracking and extrapolation algorithm needs to be applied to the C-band radar precipitation field. For the spatial interpolation, the polar grid of the X-band radar is used. Each X-band radar pixel gets assigned the reflectivity value of the C-band precipitation field. For the spatial interpolation, the polar correction. Because of the simple addition of the correction function to the high-resolution X-band measurements, the small-scale structure of reflectivity is kept compared to C-band measurements. Only in the case of extinction of the signal due to very strong attenuation do coarser-resolution data from C-band radar need to be used as the best possible approximation to fill the remaining data gaps.

4. Results

The performance of the HB attenuation correction and the isotonic regression of the ratio of reflectivities from both systems are investigated in the following. To give a

with $y_1 \leq y_2 \leq \cdots \leq y_n$ (see, e.g., Barlow and Brunk 1972). In this study we use a simple unweighted linear-ordered isotonic regression, the so-called pool adjacent violators algorithm (PAVA). In this case all weights are equal to one. PAVA solves the minimization problem iteratively and is based on the following theorem for an optimal solution:

$$\text{if } a_i \leq a_{i-1}, \text{ then } y_j = y_{j-1} \text{ with } i = 2, \ldots, n.$$  

(10)

If this constraint is violated in the first step of the iteration and $a_i > a_{i-1}$, then a new index $j = i$ is set. Then $a_i$ and $a_{i-1}$ are merged to a new value $a'_{j-1}$ with a new weight $w'_{j-1}$ according to the following:

$$a'_{j-1} = \frac{w_j a_j + w_{j-1} a_{j-1}}{w_j + w_{j-1}},$$  

(11a)

$$w'_{j-1} = w_j + w_{j-1}, \text{ and}$$  

(11b)

$$j = j - 1.$$  

(11c)

The constraint of (10) is tested again using $a'_{j-1}$, $a_j$, $w'_{j-1}$, and $w_j$. When the constraint is met, the value of $a'$ and its position $i$ are kept and $i$ is increased by 1 for the next iteration step. This procedure is repeated until no violations of the constraint in (10) are left. Finally, the values of $a'$ are assigned to their corresponding position $i$ in the function $y$.

In this study isotonic regression is performed for $K_{\text{max}}$ along each radar radial and for each time step. Isotonic regression $K_{\text{IR}}$ of $K_{\text{max}}$ along an exemplary radar radial is presented as the blue line in Fig. 2. For obtaining logarithmic attenuation–corrected reflectivities $\text{dB}Z_{X,\text{corr}}$, this function is then added to measured radial X-band reflectivities $\text{dB}Z_X$, defined as

$$\text{dB}Z_{X,\text{corr}} = \text{dB}Z_X + K_{\text{IR}}.$$  

(12)

FIG. 2. Isotonic regression (blue line) of $K_{\text{max}}$ (black crosses) along a radar radial.
better impression of the performance of the different methods, both algorithms are applied exemplary to a single reflectivity scan. Then statistical analyses are carried out for nine case studies, including stratiform, convective, and mixed events. Finally, a long-term study comprising all rain events from May to September 2013 is presented.

a. Single scan

First, the two attenuation correction algorithms are applied to a reflectivity field derived from the northernmost radar [Hungrier Wolf Tower (HWT)] of the X-band radar network at 1304 UTC 13 May 2013. A rain front, ~60 km wide, extended over northern Germany from north to south with maximum reflectivities of 45 dBZ over the network area (Fig. 3). Reflectivity fields of the X-band radar are corrected for background noise, calibrated using MRR observations, and a number of clutter filters are applied. Resulting data gaps caused by clutter detection algorithms are interpolated. A detailed description of all applied algorithms and filters can be found in Lengfeld et al. (2014).

A comparison of reflectivity measurements from X-band radar HWT in Fig. 4a and from C-band radar refined to the spatial resolution of the X-band radar in Fig. 4b underlines the strong influence of attenuation in the X-band frequency range. Close to radar HWT both systems observe similar values of reflectivity but with increasing distance radar HWT underestimates reflectivity up to complete attenuation. Figure 5 shows the profile along the 16° azimuth angle of the X-band radar reflectivity field as measured by the C-band radar (black solid line) and the X-band radar HWT (dashed light blue line). The C-band radar is less affected by attenuation and observes reflectivities up to 40 dBZ at the outer range of radar HWT. The overestimation of C-band reflectivities by the X-band radar in the first range gates is an artifact of interpolation. In the near field of the radar, many range gates are affected by clutter. Therefore, their measurements are not valuable and are eliminated. To apply the HB correction method, these gaps need to be filled by interpolating observations from neighboring range gates. In this case the C-band observations show a local minimum at the X-band radar location that cannot be anticipated by the interpolation resulting in overestimations. Differences between both systems in the following range bins could be caused by a spatial and temporal mismatch due to different scanning strategies. In Lengfeld et al. (2014) it has been shown that the standard deviation of X-band radar reflectivities within a C-band radar pixel can be up to 3 dB.

Another possible source of uncertainty is the calibration of both systems. The X-band radar has been calibrated based on MRR measurements, while calibrated power meters and signal generators are used for calibration of the C-band radar. This uncertainty may have an influence on the HB method because it is highly sensitive to calibration error. The proposed method using a combination of both systems does not depend on perfectly calibrated radars and is expected to nevertheless obtain valuable results.

The attenuation effect is also clearly visible in the field of reflectivity differences between C- and X-band radars in Fig. 6a with larger differences in regions of higher reflectivity values (cf. Fig. 4b). The X-band radar underestimates C-band reflectivity measurements in areas of highest reflectivities by up to 20 dB. The mean difference between both X- and C-band systems amounts to 5.5 dB and is mainly caused by attenuation. On the other hand, radar HWT can resolve the structure of the rain event in much more detail than the coarser-resolved C-band radar. Nevertheless, a high standard deviation of 7.25 dB between both fields is not only due to variability within a C-band radar grid cell, but also caused by attenuation. Therefore, it is of great importance to apply a method that accounts correctly for attenuation but keeps the small-scale structure of the X-band radar observations.

First, the HB algorithm is applied using reflectivity measurements of X-band radar HWT. Specific attenuation $k$ and PIA are calculated according to (4) and (6), respectively (Figs. 4c,d, respectively). Values for $k$ are up to 0.3 dB km$^{-1}$. This is in good agreement with the theoretical curve shown in, for example, Doviak and Zrnić (1993). Because of the short maximum range of 20 km and a range resolution of 0.06 km, it yields only low PIA. In northwestern and southeastern directions, where moderate reflectivity values are observed, PIA is less than 1 dB. In the northern and southern directions, the radar beam propagates through heavier precipitation
and therefore the PIA increases up to 1.5 dB. With increasing PIA, the PIA factor $A$ decreases, leading to higher values in the corrected reflectivity field in Fig. 4e than in the measured reflectivity field in Fig. 4a. Nevertheless, the X-band radar used in the study shows more attenuation and the classical approach for attenuation correction is not sufficient here. Compared to Fig. 4b reflectivity farther away from the radar is still underestimated, resulting in differences of up to 20 dB (Fig. 6b). This leads to a smaller mean negative bias of $-5.1$ dB and a standard deviation of 7.1 dB compared to the uncorrected X-band radar measurements. Also, the profile of corrected reflectivity along 16$^\circ$ azimuth (dotted dark blue line in Fig. 5) shows only little improvement in the range gates farther away from the radar. Additionally, this method can get unstable in case of large-scale heavy precipitation or due

![Image](http://journals.ametsoc.org/jtech/article-pdf/33/11/2315/3385822/jtech-d-15-0091_1.pdf)
to contamination by clutter (see section 4b). Therefore, using only the X-band radar itself for attenuation correction is not sufficient.

The newly proposed method for attenuation correction combines both X- and C-band radar reflectivity measurements and is independent of uncertainties induced by calibration errors in the X-band radar. The field of maximum apparent attenuation $K_{\text{max}}$ [as calculated from (8)] in Fig. 7a shows values of up to 20 dB at the outer parts of the radar-covered area. Because of imperfectly calibrated radar systems and clutter removal, $K_{\text{max}}$ is not a monotonically increasing function with increasing distance to the radar or might even yield negative values (data gaps in Fig. 7a). Therefore, isotonic regression as proposed in (9)–(11) is performed, leading to the regressed $K_{\text{max}}$ field in Fig. 7b, where $K_{\text{max}}$ monotonically increases with increasing distance to the radar to the highest values in the very western portion of the covered area. The $K_{\text{max}}$ field is then added to the dBZ field of X-band radar HWT (Fig. 7c).

The obtained attenuation-corrected dBZ field is in very good agreement with C-band observations from Fig. 4b with regard to absolute values. The reflectivity profile along 16° azimuth angle of 1304 UTC 13 May 2013 on the X-band radar grid as measured by DWD C-band radar (black solid line), X-band radar HWT (dashed light blue line), corrected for attenuation using the HB method (dotted dark blue line), and isotonic regression (dotted red line) is shown in Fig. 5. It is in very good agreement with the reflectivity profile obtained from the C-band radar in the areas affected by attenuation, but it preserves the small-scale variation observed by the X-band radar. Even at large distances from the radar with high attenuation effects, both dBZ fields are in good accordance. The mean bias between both systems amounts to only 0.35 dB with a standard deviation of 4.2 dB, which corresponds to a reduction of...
40% compared to the uncorrected X-band reflectivity field. Furthermore, the corrected X-band reflectivity field shows much more detail of the precipitation event than the C-band radar.

To demonstrate that the spatial variability in the corrected reflectivity field (Fig. 7c) is strongly related to the variability in the originally measured reflectivity field (Fig. 4a), a correlation coefficient between both fields is calculated along the radar radials. The correlation coefficient is calculated for the differences between the measurements with an original spatial resolution of 60 m and measurements averaged along the radar radial over a moving window of 1 up to 50 range gates (equivalent to 60 m up to 3 km). Therefore, only small-scale variations are taken into account and the influence of attenuation is neglected. The results for 18 different azimuth angles in Fig. 8 show very good agreement between the spatial variability in attenuated and corrected data with correlation coefficients of more than 0.92 in 90% of the cases. Only for an azimuth of 30° is the correlation coefficient lower, because of complete attenuation at the outermost range bins. The correlation averaged over all 360 azimuth angles (black dashed line) is between 0.97 and 0.98. For most azimuth angles, the correlation is constant over all averaging windows, indicating that the small-scale structure of the original measurements is preserved in the corrected data.

b. Case studies

To investigate the robustness of the isotonic regression method for attenuation correction and its...
applicability in different kinds of precipitation, nine case studies have been investigated, including the following three precipitation events: stratiform, convective, and mixed (stratiform, but with convective cells). Attenuated and corrected radar data are compared to MRR observations to evaluate the performance of the algorithm. Seven MRRs are operational within the PATTERN network north of Hamburg (see Fig. 1). The northernmost radar HWT is chosen for the comparison because it covers all seven MRRs. However, the radar range gate at MRR Quarnstedt (QNS) is affected by clutter and MRR HWT is located in the near field of the X-band radar. Therefore, MRR QNS and HWT are excluded from the comparison. For each event precipitation type, the time period and number of radar–MRR pairs before and after applying attenuation correction using the single-polarized X-band radar method and the isotonic regression are given in Table 2.

The first stratiform event (S1) on 25 May 2013 includes more than 5000 radar–MRR pairs. The second event (S2) took place on 13 June 2013 and comprises more than 2500 data pairs. Both were moderate events with reflectivities of up to 40 dBZ measured at the MRR sites. The third stratiform event (S3) on 19 June 2013 was stronger with reflectivities of up to 45 dBZ. The three convective case studies (C1 on 13 May, C2 on 15 May, and C3 on 15 June 2013) consist of fewer radar–MRR pairs due to the spatially more limited spread of convective events but higher reflectivity values of up to 50 dBZ. M1–M3 are mixed cases where both stratiform and convective precipitation occur during the event. Each one includes more than 1100 radar–MRR pairs. For M1 and M2, more than 95% of the measured reflectivities are lower than 35 dBZ, which indicates summer precipitation events with low to moderate rainfall. The last case (M3) is 9 h of drizzle, including some weak convective cells on 10 September 2013.

For all nine cases, the HWT X-band radar underestimates the MRR measurements, resulting in a negative bias in Fig. 9 (circular markers), but the correlation, indicated by the marker color, is more than 0.9 in seven of the nine cases. The convective events C1–C3 show very similar results with biases around −4.1 dB mainly caused by attenuation and root-mean-square errors (RMSEs) between 5.4 and 5.85 dB are shown as gray error bars. For stratiform cases S1 and S2 RMSEs are distinctly lower, because of less spatial and temporal variability within the precipitation field. During case S3 the radar measurements were affected by disturbances due to external emitters, leading to a comparably low correlation of 0.64 and a high bias and RMSE (−5.64 and 7.76 dB, respectively). HWT is in better agreement with the MRRs during the mixed cases M1–M3 than during the convective cases with biases less than −3.8 dB and RMSEs smaller than 4.25 dB, but the influence of attenuation is evident here as well.

Applying the HB attenuation correction algorithm based on only single-polarized X-band radar data leads to smaller biases in all nine cases. However, because of the instability of the algorithm, there is a loss of data of up to 57% for C3 compared to the original dataset, indicated by smaller marker sizes. This also leads to distinctly higher RMSEs and a lower correlation between X-band radar HWT and MRRs. The highest correlation is obtained for S1 with 0.74. Therefore, this method is not practical for the type of short-range high-resolution X-band radars investigated in this study.

The isotonic regression method corrects very well for attenuation and reduces the bias to less than ±1 dB in all nine cases. The good correlation between HWT and MRRs is maintained and the RMSE reduced. The results for mixed and stratiform events (except for the disturbed event, S3) are very promising with correlations of more than 0.9 and RMSEs less than 2.2 dB. But

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<td>1750</td>
</tr>
<tr>
<td>M3</td>
<td>Mixed</td>
<td>0600–1500 UTC 10 Sep 2013</td>
<td>1334</td>
<td>745</td>
<td>1407</td>
</tr>
</tbody>
</table>
also for convective cases with more internal variability the RMSEs are reduced between 10% (C2) and 25% (C3). Correlations of 0.87 and 0.9 for C1 and C3, respectively, are still satisfying and indicate that the small-scale variations in the X-band radar data are preserved by the isotonic regression. Poorer correlation of only 0.77 for C2 is caused by the fact, that in this case the radar signal has been attenuated completely by strong precipitation. Therefore, measurements with coarser resolution from C-band radar fill these areas of complete attenuation, leading to lower correlation.

c. Long-term study

Additionally, a long-term comparison of X-band radar and MRR observations has been carried out for all precipitation events that occurred between 1 May and 30 September 2013. The comparison of attenuated reflectivity measurements from HWT to MRR observations at the corresponding height levels in Fig. 10a indicates the influence of attenuation due to liquid water. HWT underestimates MRR measurements, especially for reflectivities of more than 20 dBZ. Despite the good correlation of 0.9, HWT underestimates the MRRs on average by −2.65 dB with an RMSE of 3.87 dB. After applying attenuation correction based on isotonic regression, the mean bias is reduced to −0.03 dB and the RMSE is reduced to 3.14 dB in Fig. 10b. The correlation between HWT and MRRs is slightly reduced but both systems are still in good agreement, even for reflectivities of more than 30 dBZ, where r is 0.88.

To underline the good agreement between X-band radar and MRR due to spatial and temporal high-resolution observations, MRR reflectivity is also compared to C-band radar measurements with 5-min temporal and 1-km spatial resolution. They show good agreement regarding mean reflectivity values with a bias of −0.77 dB. In contrast to the X-band radars, the comparison of C-band radar reflectivity with MRR observations in Fig. 10c shows much more variability with an RMSE of 4.59 dB. The correlation between both systems amounts to 0.73. This variability originates from the relatively coarse temporal and spatial resolution of the C-band radar observations in comparison to the point measurements of MRR with 10-s temporal resolution. The correlations between MRR observations and X-band radars remain nearly constant before and after attenuation correction and are distinctly higher than the correlation between MRR and the C-band radar. This indicates that after applying the proposed attenuation correction, the fine spatial and temporal structures remain in the X-band reflectivity field.

All events are classified by manual inspection as either stratiform, convective, or a mixture of both in order to investigate the performance of the correction algorithm in different kinds of precipitation. For all three precipitation types, the influence of attenuation is clearly visible in the X-band radar data, leading to underestimation of MRR measurements between −1.97 dB for convective rain (Fig. 11c) and −3.34 dB for stratiform rain (Fig. 11a). The X-band radar reflectivity measurements hardly exceed 30 dBZ. Despite the bias, the temporal variability of the precipitation events is observed very well by the X-band radar. Best accordance arises in mixed cases with a correlation of 0.95 (Fig. 11e). In convective cases with the highest spatial and temporal variability, the correlation between X-band radar and MRR is still strong, with a value of 0.89. The attenuation correction with isotonic regression reduces the mean bias for all three precipitation types to less than ±0.83 dB (see Figs. 11b,d,f). The underestimation of high reflectivity values is compensated, and the good correlation between X-band radar and MRRs is preserved. Overall, the new attenuation correction method works best for mixed cases, where convective cells are embedded in stratiform precipitation, but it performs almost comparably well for the stratiform and convective cases.

5. Conclusions

In this paper a simple method to correct for attenuation in reflectivity measurements of X-band radars is
presented that is applicable in basically every region covered by C- or S-band radars. It combines the advantages of more accurate long-range systems with high-resolution observations from local X-band radars. Observing precipitation with radars operating in the X-band frequency range has the advantage of low cost due to small antenna size compared to C- and S-band radars, and high temporal and spatial resolution with less than 1 min and 100 m, respectively. This is of great importance, especially in heterogeneous regions such as urban areas. The downside is the high influence of attenuation by liquid water in this frequency range. Therefore, precise estimation of attenuation is mandatory for obtaining valuable precipitation estimates.

Common algorithms, for example, based on Hitschfeld and Bordan (1954), tend to underestimate attenuation in heavy precipitation or become unstable. Delrieu et al. (1997) implemented mountain returns in their algorithm to restrict and stabilize the attenuation correction, but it also limits the area where the method is practicable to regions with at least one mountain. In contrast, most countries are covered by nationwide C- or S-band radar networks. Therefore, a simple method is proposed combining reflectivity observations from C- and X-band radars for attenuation correction. The performance of this method is investigated by comparing the results to a single-polarized X-band correction method.

A study of a single scan of X-band radar reflectivity measurements during a precipitation event on 13 May 2013 assesses the performance of the novel method compared to the HB algorithm. Hereby, specific attenuation $k$ and path-integrated attenuation (PIA) are calculated from the reflectivity field derived from X-band radar. Despite good agreement with theoretical curves of $k$, the attenuation of the X-band radar systems used in this study is underestimated. Therefore, also reflectivities are still underestimated compared to C-band radar observations. In areas of maximum precipitation and therefore maximum attenuation, the method can get unstable and does not provide reliable results. Hence, for the X-band radar type used in this study, a different method for attenuation correction is required.

The new attenuation correction method based on the logarithmic ratio of reflectivities from C- and X-band radars ($K_{max}$) produces promising results. Estimation of $K_{max}$ indicates attenuation of up to 20 dB at the outermost range gates of the X-band radar for the heavy precipitation event on 13 May 2013. Because of calibration errors and other disturbances in radar observations, $K_{max}$ is not monotonically increasing with increasing distance to the radar. To account for this unphysical behavior, isotonic regression is performed. The derived monotone function is then added to

![Fig. 10. Long-term comparison of X-band radar HWT and the DWD C-band radar with MRRs within the PATTERN region from 1 May to 30 Sep 2013: (a) original X-band reflectivity measurements, (b) attenuation-corrected reflectivity measurements using the isotonic regression method, and (c) C-band reflectivity measurements. White indicates boxes containing less than 0.001% of the dataset.](http://journals.ametsoc.org/doi/abs/10.1175/JTECHEL-W-13-0091.1)
measured logarithmic reflectivity of the X-band radar. This correction method provides dBZ fields that are in good agreement with fields from the C-band radar but with much higher spatial and temporal resolution. The correlation of the differences between reflectivity along a radar radial in original spatial resolution and averaged over certain distances for attenuated and corrected data reveals that the isotonic regression preserves the spatial structure of the highly resolved reflectivity field as measured by the X-band radar.

![Image of radar reflectivity diagrams](https://example.com/image.png)

**Fig. 11.** Long-term comparison of X-band radar HWT with MRRs within the PATTERN region from 1 May to 30 Sep 2013: (left) original X-band reflectivity measurements and (right) attenuation-corrected reflectivity measurements using the isotonic regression method. (a),(b) All stratiform X-band radar-MRR pairs; (c),(d) convective cases; and (e),(f) mixed cases. White indicates boxes containing less than 0.001% of the dataset.
Nine case studies consisting of three convective, three stratiform, and three mixed (convective and stratiform) precipitation events demonstrate that the isotonic regression method performs well in all kinds of rain. Underestimation from X-band radar compared to five Micro Rain Radars (MRRs) is reduced to less than 1 dB and high correlation between both systems remains. A comparison with MRRs for all precipitation events between 1 May and 30 September 2013 underlines the good performance of the proposed method. Despite a high correlation of 0.9, uncorrected X-band measurements have a negative bias of −2.65 dB and an RMSE of 3.87 dB. After applying the proposed attenuation correction, the correlation is still high with 0.88, the bias is reduced to −0.03 dB, and the RMSE is reduced by 20% to 3.14 dB. However, C-band radar and MRR show a lower correlation of 0.73 and a higher RMSE of 4.59 dB for the same period due to the coarser resolution of the C-band radar observations. This indicates that using C-band radar data for attenuation correction does not affect the high spatial and temporal resolution of the X-band radar reflectivity field.

This simple attenuation correction method proposed here already shows good and encouraging results and is suitable in every region covered by C- or S-band radars. Small-scale structures of precipitation events, which can be observed by high-resolution X-band radars, are preserved as are reflectivity values and therefore rain rates can be estimated more precisely. This can be valuable, especially in urban areas for more exact nowcasting of precipitation and rainfall–runoff simulation to forecast floods, enhance risk management, and prevent damage. Nevertheless, there are several possibilities for improving its performance in the future; for example, different sampling volumes and heights of both radar systems induce uncertainties. Applying vertical profile of reflectivity (VPR) correction using profiles from MRRs and from C-band radar would allow for calculating the attenuation at a common height. Another source of uncertainty is the temporal mismatch. The C-band system operates with a temporal resolution of 5 min, and the X-band system provides a measurement every 30 s. For postprocessing a weighted temporal average of the C-band observations is used, but for future real-time applications, nowcasting needs to be implemented in the attenuation correction scheme in order to obtain the corresponding reflectivity field from C-band radars.

Acknowledgments. The project Precipitation and Attenuation Estimates from a High-Resolution Weather Radar Network (PATTERN) is a joint project between the University of Hamburg and the Max Planck Institute for Meteorology. It is funded by the Deutsche Forschungsgemeinschaft (Grant AM308/3-1). The authors thank the German Weather Service (DWD) for making products of their C-band radar network available for research purposes within the project PATTERN.

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