Reanalysis of multi-year high-resolution X-band weather radar observations in Hamburg

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Abstract. ~~Operational rain gauge networks provide reliable local precipitation measurements, but are unable to represent rainfall variability for large domains at small temporal scales~~This paper presents an open-access data set of reanalysed radar reflectivities and rainfall rates at sub-kilometre spatial and minute temporal scale. Variability at these scales is a blind spot for both operational rain gauge networks and operational radar networks. In the urban area of Hamburg, precipitation measure­ments of a single-polarized X-band weather radar operating at a high temporal ($30\,$s), range ($60\,$m), and azimuthal sampling ($1°$) resolution are ~~available for~~ made available for a period of more than eight years. ~~These measurements refine observations of the German nationwide C-band radars within the 20 km scan radius. Studies on short time periods (several months) prove the performance of this low-cost local area weather radar. A case study on a tornado in a rain event demonstrates its refined resolution compared to the German nationwide C-band radars~~

We describe in detail the reanalysis of the raw radar data, outline the radar performance for the years 2013 to 2021, and discuss open issues and limitations of the data set. Several sources of radar-based errors were adjusted gradually affecting the radar reflectivity and rainfall measurements, e.g. noise, alignment, non-meteorological echoes, radar calibration, and attenuation. The deployment of additional vertically pointing micro rain radars yields drop size distributions at ~~relevant heights~~the radar beam height, which reduces errors effectively concerning the radar calibration and ~~required statistical relations (k-Z and Z-R relation)~~attenuation correction, and monitors the radar data quality.

~~This paper describes an open-access data set covering reanalysed~~ A statistical evaluation revealed that X-band radar reflectiv­ities and rainfall ~~estimates measured by an X-band radar at high spatio-temporal resolution in~~ rates are in very good agreement with the micro rain radar measurements. Moreover, the ~~urban environment of Hamburg between 2013 and 2021. Additionally, this paper outlines the performance of this X-band radar for long time periods, and discuss open issues and limitations~~ analyses of rainfall patterns shown for an event and accumulated rainfall of several months prove the quality of the data set.

The provided radar reflectivities facilitate studies on attenuation correction and the derivation of further weather radar prod­ucts, like an improved rainfall rate. The rainfall rates ~~will~~ itself can be used for studies on the spatial and temporal scale of precipitation and hydrological research, e.g. input data for high-resolution modelling, in an urban area.

1 Introduction

25 Knowledge of small-scale rainfall variability is needed for several meteorological and hydrological applications, particularly in urban environments due to its water-related sensitivity. For instance, urban hydrological applications demand high-quality radar rainfall data with at least a temporal resolution of $1\,\mathrm{min}$ and spatial resolution of $100\,\mathrm{m}$ (Einfalt et al., 2004; Berne and Krajewski, 2013; Gires et al., 2013; Ochoa-Rodriguez et al., 2015; Thorndahl et al., 2017). In general, hydrometeorological and fundamental studies on rainfall properties may benefit from long-term measurements at small spatio-temporal scales.

30 Rain ~~gauges~~ gauge networks provide reliable local precipitation measurements, but due to its limited operational network densities, they are unable to represent rainfall variability for large domains at small temporal scales (e.g. Berne et al., 2004; Villarini et al., 2008; Lengfeld et al., 2019; Maier et al., 2020). Conventional weather radar systems, mostly operating at S- and C-band frequencies, are able to provide radar rainfall measurements over large domains with a temporal resolution of several minutes and spatial resolution of a few hundred meters. Long-term radar based precipitation climatologies based on

35 these conventional radars are available for Germany with a $5\,\mathrm{min}$ temporal and $1\,\mathrm{km}$ spatial resolution (Winterrath et al., 2018), and for Europe with an hourly temporal and $2\,\mathrm{km}$ spatial resolution (Overeem et al., 2023). Consequently, there is a gap in long-term radar rainfall data sets at the sub-kilometre spatial scale and temporal scales below five minutes. X-band radars are able to refine rainfall estimates at temporal resolutions down to $16\,\mathrm{s}$ (van de Beek et al., 2010) and radial resolutions down to $3\,\mathrm{m}$ (Mishra et al., 2016), but most of them operate at or below $100\,\mathrm{m}$ spatial and ~~$1\,\mathrm{m}$~~ $1\,\mathrm{min}$ temporal resolution in areas

40 of special interest, like urban areas (e.g. Ventura and Russchenberg, 2009; van de Beek et al., 2010; Wang and Chandrasekar, 2010; Maesaka et al., 2011; Berenguer et al., 2012; Allegretti et al., 2012; Lengfeld et al., 2014; Lo Conti et al., 2015; Yoon et al., 2017; Hosseini et al., 2020; Schleiss et al., 2020). However, long-term reanalyses of these radar observations are not available. Therefore, the aim of this paper is to present the data reanalysis of X-band radar observations at the sub-minute and hectometre scale in the urban area of Hamburg for multiple years, which resulted in an open-access data set of radar

45 reflectivities and rainfall estimates (Burgemeister et al., 2024).

The operational, single-polarized X-band weather radar monitors precipitation within a $20\,\mathrm{km}$ scan radius around Hamburg's city centre since 2013, operated in synergy with two micro rain radars (MRRs) and rain gauges. The local area weather radar (LAWR) operates at one elevation angle with a high temporal ($30\,\mathrm{s}$), range ($60\,\mathrm{m}$), and azimuthal sampling ($1°$) resolution, refining coarser observations of the German nationwide C-band radars at $250\,\mathrm{m}$ spatial and $5\,\mathrm{min}$ temporal resolution. Although

50 most of the latest X-band radars have dual-polarimetric capabilities (e.g. Anagnostou et al., 2018; Schleiss et al., 2020; Neely III et al., 2021; Pejcic et al., 2022; Cao et al., 2023; Hosseini et al., 2023), where dual-polarimetric quantities improve rainfall estimates, even low-cost, single-polarized X-band radars provide valuable information on the spatio-temporal variability of precipitation (e.g. van de Beek et al., 2010; Lo Conti et al., 2015; Marra and Morin, 2018). The single-polarized X-band radars require extensive post-processing and the deployment of independent additional sensors, like micro rain radars, disdrometers

55 or rain gauges (Villarini and Krajewski, 2010; Thorndahl et al., 2017). Former studies on short time periods (several months and a case study) show that the LAWR provides detailed information on the structure of precipitation. Lengfeld et al. (2014) deployed a network of four LAWRs and micro rain radars in a rural area of northern Germany. They describe correction

algorithms for single and networked LAWRs and discuss the performance of measurements of five months. Lengfeld et al. (2016) and Lengfeld et al. (2018) introduce a method to correct reflectivity measurements for attenuation using less attenuated radars, and compare attenuation correction methods for single-polarized X-band radars using this LAWR network. The LAWR network was dismantled in 2017. However, the LAWR located in Hamburg is still in operation, extending a unique data set. Hoffmann et al. (2018) shows that the LAWR is able to capture the circular pattern in ~~rain~~ rainfall rates because of its higher resolution in space and time. In a recent study, a LAWR was deployed to provide rainfall estimates for studies on cold pool events during the Field Experiment on Sub-mesoscale Spatio-Temporal Variability in Lindenberg (FESSTVaL) from June to August 2021 (Burgemeister et al., 2022). The previous studies provide knowledge and algorithms to reanalyse a consistent long-term data set based on LAWR measurements.

Any user of the presented long-term data set of homogeneously reanalysed rainfall estimates from X-band radar observations will need to know the details on data processing, availability and accuracy. In this paper, we describe the setup of the LAWR in synergy with two MRRs and rain gauges in Hamburg (Sect. 2). We explain the reanalysis of the multi-year measurements, addressing the noise removal, correction of non-meteorological echoes, calibration, attenuation correction, and rainfall estimation (Sect. 3). Finally, we check the performance of the multi-year measurements with MRRs observations, present rainfall patterns, and discuss limitations of the data set (Sect. 4).

2 Radar observations in Hamburg

In the urban area of Hamburg, synergistic precipitation observations of a local area weather radar (LAWR) operating at X-band frequency, a micro rain radar (MRR) and a rain gauge (RG) are available since 2013 (Fig. 1). The measurements can refine the observations of the German nationwide C-band radars, and supplement and cover additional rain gauges. The LAWR Hamburg Geomatikum (HHG) is located on the rooftop of the Meteorological Institute of the Universität Hamburg in the centre of Hamburg. The MRR Wettermast Hamburg (WMH) is located at the scientific measuring site of the Meteorological Institute of the Universität Hamburg in the south-eastern part of the city. The MRR Blankenese Bauersberg (BBG) is deployed at a waterworks of the municipal water and wastewater utility Hamburg Wasser in the west of Hamburg since December 2017. The MRR WMH and LAWR HHG are $10.1\,\mathrm{km}$ apart. The MRR BBG and LAWR HHG are $12.3\,\mathrm{km}$ apart. The closest C-band radar of the German Weather Service (DWD) covering the whole measuring area of the LAWR HHG was in Hamburg Fuhlsbüttel (airport) with a distance of $7.3\,\mathrm{km}$ until 2014 and is since then in Boostedt $48.7\,\mathrm{km}$ away.

2.1 X-band weather radar

The LAWR is a modified ship navigation radar of type GEM scanner SU70-25E. This single-polarized X-band radar operates at a frequency of $9.41\,\mathrm{GHz}$. The LAWR provides horizontally radar reflectivity measurements at one fixed elevation angle with $30\,\mathrm{s}$ temporal, $60\,\mathrm{m}$ range, and $1°$ azimuthal sampling resolution. The elevation angle was adjusted several times within the years for optimal operation during maintenance to reduce disturbances by non-meteorological echoes. The advantages of the LAWR are its low costs, high spatio-temporal resolution, and scanning strategy (Lengfeld et al., 2014). The LAWR costs less
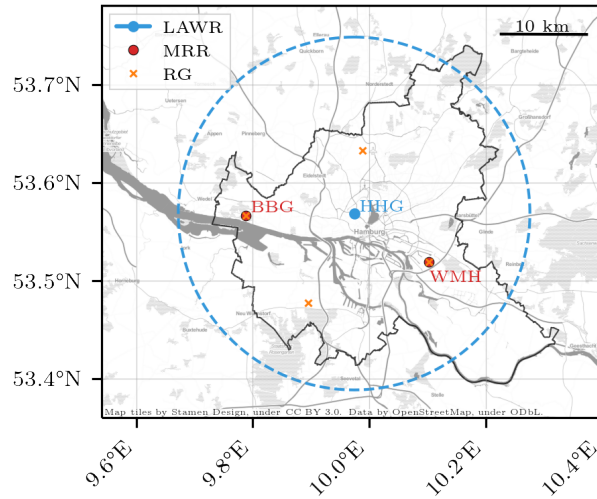
Figure 1. Precipitation observations in Hamburg. The location of the local area weather radar (LAWR) / X-band radar (WRX) on the rooftop of the building "Geomatikum" in Hamburg (HHG) is indicated with a blue point. The blue dashed line shows the coverage with the 20 km scan radius. The locations of two micro rain radars (MRRs, red points) are by name Blankenes Bauersberg (BBG) and Wettermast Hamburg (WMH). Rain gauges (RGs, orange crosses) are located next to the MRRs and at sites of the German Weather Service (DWD).

Table 1. Technical LAWR specifications (Lengfeld et al., 2014)

	Specification
Range resolution	60 m
Temporal resolution	30 s
Scan radius	20 km
Angular resolution	2.8°
Azimuthal sampling resolution	1°
Beam width	2.8°
Transmit power	25 kW
Frequency	9.41 GHz
Pulse width	0.4 µs
Pulse repetition frequency	800 Hz
Rotation speed	24 rpm

than 20% than conventional X-band radars. The radar reflectivity represents an $30\,\text{s}$ average of approximate 67 pulses per $1°$ collected during 12 sweeps, whereas conventional weather radars provides instantaneous measurements based on one sweep. The LAWR specifications are summarized in Table 1 and for technical details to the radar, refer to Lengfeld et al. (2014).

2.2 Micro rain radar

The MRR is a vertically pointing frequency-modulated-contionus wave (FM-CW) Doppler radar manufactured by METEK Meteorologische Messtechnik GmbH (Peters et al., 2002). The MRR retrieves drop size distributions (DSDs) from measured Doppler spectra using the terminal fall velocity given by Atlas et al. (1973). Rainfall rates and radar reflectivities are calculated from DSDs (Doviak et al., 1993). Noise and attenuation corrections are performed by the manufacturer's software (Metek, 2015). The DSD retrieval assumes stagnant air. Vertical wind and turbulence effects are discussed in Peters et al. (2005) and are neglected in this study. The transmit frequency is at $24.23\,\text{GHz}$ (K-band). Before November 2014 the MRR WMH measured with a transmit frequency of $24.0\,\text{GHz}$. Both MRRs measure DSD profiles for 31 range gates, with a range resolution of $35\,\text{m}$ and a temporal resolution of $10\,\text{s}$. Adjacent rain gauges monitor the MRR's performance.

3 Data reanalysis

Precipitation data sets that are generated by operational data processing are prone to inconsistencies and breaks, e.g. introduced by advancement in the processing algorithms or delayed calibration after hardware changes. As a decisive advantage, this reanalysis radar data set is based on a set of consistent, state-of-the data processing procedures. To ensure traceability, we document in this section the essential data processing procedures: removal of noise (Sect. 3.1), correction of misalignment (Sect. 3.2), detection of non-meteorologial echoes (Sect. 3.3), radar calibration (Sect. 3.4), correction of attenuation (Sect. 3.5), and the conversion to rainfall rates by a Z-R relation (Sect. 3.6). The availability of corrected radar reflectivities and rainfall estimates will finally be summarized in the last section (Sect. 3.7).

3.1 Remove noise

The raw radar reflectivities measured by the LAWR are superimposed by microwave noise that comes from the atmosphere and the radar itself. The radar cannot measure the background noise directly, however, an accurate estimation of the noise is mandatory to detect also weak weather signals. The background noise removal is dynamically fitted for every $30\,\text{s}$ time step following Lengfeld et al. (2014). In contrast to the received signal, which is proportional to the squared distance r^2 to the radar, the background noise is range-independent. Therefore, the radar reflectivity factor Z is multiplied by r^{-2} and an initial guess of the noise level estimated from a rain-free field is subtracted from the radar field $Z \cdot r^{-2}$. The noise level is multiplied by a factor of 1.03 to remove all noise artefacts. If more than $10\,\%$ of the radar bins remain rain-free, the 10th percentile of the original $Z \cdot r^{-2}$ is the next noise level , otherwisebecomes the new noise level estimate; otherwise, the noise level from the prior time step is kept. The estimated noise level is used as an initial guess for the next time step. The recent 10 noise level estimates are averaged to stabilize the algorithm regarding radar artefacts. Finally, the dynamic background noise is subtracted from the radar field, yielding the noise-free radar reflectivity factor after the multiplication by r^2.
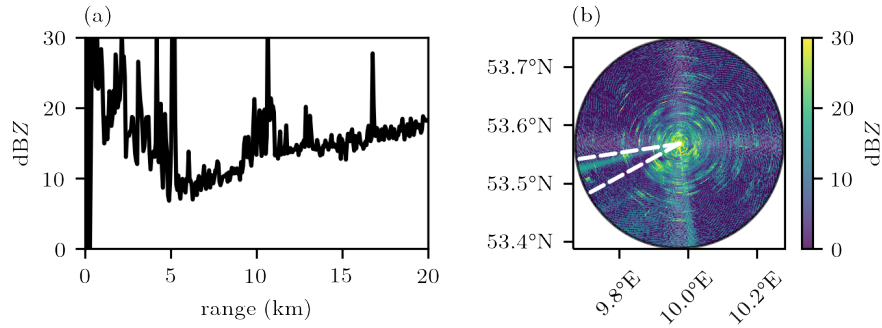
Figure 2. Radar reflectivity after noise removal at sunset, 02.03.2020 16:20 UTC. (a) Radar reflectivity at the $255.5°$ azimuth angle representing the solar signal. (b) Radar reflectivity with continuos signal over range which is visible during the sun set. The white lines indicate a $20°$ window around the true sun position in the radar azimuth angle.

3.2 Determine radar alignment

The radar alignment of LAWR was adjusted manually at installation and after maintenance, leading to unknown uncertainties in antenna pointing. Since the beginning of operational measurements of the LAWR, spokes in radar reflectivity are observed
125   in the direction of the sun during sunrise and sunset (Fig. 2). These solar signals facilitate the subsequent determination of the antenna azimuth α and the beam elevation angle ε (Huuskonen and Holleman, 2007), using the known position of the sun (Stafford, 2021; Reda and Andreas, 2008).

The solar signal in radar reflectivity is the strongest spoke in direction of the sun position and is determined empirically in the radar reflectivity after noise removal during rain-free events. The ~~continues~~ continuous maximal reflectivity (Fig. 2) is
130   detected at 3658 sunrises and sunsets during $23\,\mathrm{min}$ on average. The mean calculated sun elevation angle of one sunrise or sunset is the radar beam elevation angle ε. The mean difference of the sun azimuth angle α_{sun} and the azimuth angle of the detected solar signal α_{detect} is the azimuth offset

$$\Delta\alpha' = \overline{\alpha_{\mathrm{detect}} - \alpha_{\mathrm{sun}}}. \tag{1}$$

The detection of one sunrise or sunset is constrained to a minimal duration of $15\,\mathrm{min}$ and maximal standard deviations of the
135   beam elevation $\sigma_{\varepsilon'} < 1°$ and the azimuth offset $\sigma_{\Delta\alpha'} < 1°$. The determined ε' and $\Delta\alpha'$ are averaged between maintenance dates, resulting in the final beam elevation angle ε and azimuth offset $\Delta\alpha$ (Table 2). Between 27.05.2013 and 11.08.2021 the radar alignment is characterized by six ε, ranging between $3.3°$ and $6.1°$, and seven $\Delta\alpha$ with a maximum of $5.6°$. The estimates of ε and $\Delta\alpha$ are stable within periods of at least two months up to several years, with a maximal standard deviation of $\pm0.4°$. The known radar alignment and thus location and height of the measurements allows comparisons with other measurement
140   devices and hence its calibration after clutter correction.

Table 2. X-band radar (LAWR) HHG alignment, defined by the beam elevation angle ε and azimuth offset $\Delta\alpha$.

Modification date	ε (°)	σ_ε (°)	$\Delta\alpha$ (°)	$\sigma_{\Delta\alpha}$ (°)
27.05.2013 14 UTC	4.4	±0.3	0.9	±0.4
12.07.2014 00 UTC	6.1	±0.1	2.5	±0.1
23.09.2014 15 UTC	4.2	±0.2	-	-
12.03.2015 14 UTC	-	-	3.2	±0.1
09.06.2015 13 UTC	5.4	±0.2	-	-
22.03.2017 15 UTC	-	-	4.1	±0.2
20.04.2018 08 UTC	-	-	3.9	±0.1
25.04.2020 16 UTC	3.3	±0.1	5.0	±0.1
03.07.2020 15 UTC	3.5	±0.1	5.6	±0.2

3.3 Detect clutter

The noise-corrected radar reflectivities contain static and dynamic non-meteorological echoes (clutter) characterized by high values and ~~artificial~~ erroneous spatio-temporal gradients. Static clutter is caused by static objects, e.g. trees and buildings. Dynamic clutter is caused by dynamic objects, e.g. planes, birds, and other radars measuring at X-band frequencies. Consequently, measurements in urban areas are more affected by clutter than in rural areas. Additionally, ship navigation radars located at the Hamburg harbour can cause interferences in form of spikes or rings. All these clutter values can not be easily detected within the LAWR measurements due to the lack of polarimetric or Doppler quantities. The clutter detection requires the application of several gradient-based and time-dependent correction algorithms.

As a first step of clutter correction, static clutter is removed by subtracting a static clutter field. Radar reflectivities and clutter are assumed to be additive. The static clutter field is estimated from the temporal median of the noise-corrected, rain-free radar reflectivity factor. A stable estimate of the static clutter field requires the measurement's stability, i.e. continuos relative calibration, alignment, adjustment of the radar receiver, which is valid over multiple weeks, months or years. Due to computing time, the static clutter field is updated on a roughly monthly basis for periods with similar clutter signals. To restrict the temporal median of the radar reflectivity factor to mainly rain-free cases, a rain threshold based on the rain fraction is introduced, represented by the fraction of radar reflectivities exceeding $5\,\mathrm{dBZ}$ for every time step. The radar reflectivity of $5\,\mathrm{dBZ}$ represents a rainfall rate R of $0.1\,\mathrm{mm\,h^{-1}}$ using a standard Z-R relationship. The rain threshold was empirically set to the 75 percentile of the rain fraction, avoiding rain patterns affecting the static clutter field. Furthermore, this threshold of the rain fraction is also dependent on the measurement's stability. Changes of the rain fraction indicate technical maintenance of the radar, which is represented by a change point of the rain fraction based on a different calibration, or technical errors of the radar receiver, which is represented by a drift of the rain fraction based on a slow reduction of radar sensitivity. The correction of static clutter using a stable estimate of a static clutter field subtracts clutter leaving the measurement, so there is no need of interpolation.

Dynamic clutter signals are removed by several gradient-based correction algorithms. Five different filter algorithms are applied: the ~~TDBZ~~ texture of the logarithmic reflectivity (TDBZ) filter (Hubbert et al., 2009), the SPIN filter (Hubbert et al., 2009), a spike filter (Lengfeld et al., 2014), a ring filter (Lengfeld et al., 2014), and a speckle filter. ~~The texture of the logarithmic reflectivity (TDBZ)~~ Since isolated clutter signals, spikes and rings vary in length and width, two variants of the spike filter, two variants of the ring filter, and five variants of the speckle filter are applied, each with different parameters.

The TDBZ filter calculates the TDBZ field as the mean of the squared logarithmic reflectivity difference between adjacent range gates according to (Hubbert et al., 2009):

$$\text{TDBZ} = \left[\sum_{i}^{N} (\text{dB}Z_i - \text{dB}Z_{i-1})^2 \right] / N \tag{2}$$

where $\text{dB}Z$ is the reflectivity and N is the number of range gates used. The TDBZ filter labels a range gate as a clutter signal if the TDBZ field exceeds $\text{TDBZ} > 9\,\text{dBZ}$ within $N = 3$ consecutive range gates. The filter was modified to computations along range gates following Lengfeld et al. (2014).

The SPIN filter detects clutter based on a measure of how often the reflectivity gradient changes sign along the radial direction according to (Hubbert et al., 2009). The reflectivity gradient and sign change is calculated between three consecutive range gates, e.g. $\text{dB}Z_{i-1}$, $\text{dB}Z_i$ and $\text{dB}Z_{i+1}$:

$$\text{sign}\{\text{dB}Z_i - \text{dB}Z_{i-1}\} = -\text{sign}\{\text{dB}Z_{i+1} - \text{dB}Z_i\}, \tag{3}$$

and

$$\frac{|\text{dB}Z_i - \text{dB}Z_{i-1}| + |\text{dB}Z_{i+1} - \text{dB}Z_i|}{2} > \text{spin\_thres}, \tag{4}$$

where spin_thres is a reflectivity threshold, which is set to $3\,\text{dBZ}$. The SPIN filter labels a range gate as a clutter signal if more than two range gates in a centred window of five range gates met the conditions of the equations 3 and 4.

The spike filter identifies clutter in the form of spikes by calculating the reflectivity gradients for consecutive radar beams. The reflectivity gradient is calculated between the reflectivity $\text{dB}Z_i$ and the reflectivities with a distance of W degrees in azimuth $\text{dB}Z_{i-W}$ and $\text{dB}Z_{i+W}$:

$$[\text{dB}Z_i - \text{dB}Z_{i-W} > \text{spike\_thres}] \wedge [\text{dB}Z_i - \text{dB}Z_{i-W} > \text{spike\_thres}] \tag{5}$$

where spike_thres is a reflectivity threshold, which is set to $3\,\text{dBZ}$. Two spike filters are applied: One spike filter is configured with the parameters $N = 3$ and $W = 1$ and the second one with $N = 11$ and $W = 2$. The spike filter labels a range gate as clutter signal if more than $50\,\%$ in a window of N consecutive radar beams meet the condition of Eq. (5). The ring filter identifies clutter in the form of rings by calculating reflectivity gradients for consecutive range gates. Consequently, the ring filter is similar to the spike filter, but computes the reflectivity gradients using Eq. (5) with a distance of W meters in range and a ring_thres of $3\,\text{dBZ}$. The ring filter labels a range gate as clutter signal if more than $50\,\%$ in a surrounding window of N range gates meet the condition of Eq. (5). Two ring filters are applied: One ring filter is configured with the parameters $N = 11$

and $W = 1$ and the second one with $N = 11$ and $W = 2$. ~~Since spikes and rings are of different length and width, two spike and two ring filters are applied to remove spikes and rings.~~

The application of one TDBZ filter, one SPIN filter, two spike filters, and two ring filters removes dominant clutter patterns, but there remain isolated clutter signals. For this purpose, the speckle filter assumes that rain areas are connected, thus consist of more than a few isolated high reflectivities. This filter counts radar reflectivities of grid cells $\mathrm{dB}Z_{i,j}$ greater than a rain threshold of $5\,\mathrm{dBZ}$ within a two-dimensional window of size $k \times l$:

$$\sum_{i=1}^{k} \sum_{j=1}^{l} \mathrm{f}(\mathrm{dB}Z_{i,j}) < \mathrm{speckle\_thres} \tag{6}$$

where $\mathrm{f}(\mathrm{dB}Z_{i,j}) = 0$ for $\mathrm{dB}Z_{i,j} \leq 5\,\mathrm{dBZ}$ and $\mathrm{f}(\mathrm{dB}Z_{i,j}) = 1$ for $\mathrm{dB}Z_{i,j} > 5\,\mathrm{dBZ}$. If the sum of Eq. (6) is smaller than the speckle_thres, the centre of the $k \times l$ window is identified as clutter. Five speckle filters are applied using different window sizes and threshold: $k = \{3, 3, 5, 5, 7\}$, $l = \{3, 5, 5, 7, 7\}$, and $\mathrm{speckle\_thres} = \{3, 5, 10, 16, 26\}$.

~~The five different clutter filter algorithms remove~~ To assess the effectiveness of these five filters, we have analysed exemplarily the clutter detection from May to September 2019: The TDBZ filter is the most effective filter by detecting $66.1\,\%$ of all clutter pixels. Many clutter pixels are as well identified by the spin filter ($25.7\,\%$) and one of the five speckles filters ($14.0\,\%$ to $31.5\,\%$). In contrast, the detection rate is low for the two spike filters ($3.1\,\%$ and $0.4\,\%$) and the two ring filters ($1.0\,\%$ and $1.4\,\%$)

Identified and removed clutter signals and yield missing values in the reflectivity field. Missing values are interpolated ~~using the kriging method~~ with ordinary Kriging (Cressie, 1993). The temporal-constant spatial covariance is modelled by a Gaussian semivariance with a length scale of $5\,\mathrm{km}$ and stationary random noise, which represents the nugget. For computational efficiency, the Kriging method is spatially localized (Wesson and Pegram, 2004) by using the 20 nearest neighbours to the grid points that should be interpolated. However, it is important to keep in mind that some clutter signals remain within the measurements and may affect the interpolation of missing radar reflectivities.

3.4 Calibrate

The observational synergy of the LAWR, MRR, and RG facilitates calibration and adjustment of the radar measurements. The MRR provides the radar reflectivity factor Z_{MRR} and rainfall rate R_{MRR} derived from drop size distributions. With Z_{MRR}, the LAWR radar reflectivity factor Z_{LAWR} is calibrated directly. The calibration and evaluation with MRR measurements has mainly three advantages: the same variable ~~, and~~ the same measuring height ~~, and more or less the same volume are compared~~ are compared at sufficient large sampling volume sizes. A calibration with a disdrometer would increase errors because of the height difference and different sampling volume sizes. The calibration with a RG would add an error based on uncertainties introduced by Z-R relationships. However, the MRR measurements are adjusted with a RG at the same location. The methodology is described by Lengfeld et al. (2014).

Before calibration, R_{MRR} and consequently Z_{MRR} are adjusted with RG measurements. The logarithmic calibration factor for the MRR C_{MRR} is derived from $3\,\mathrm{h}$ averages of R_{MRR} at $105\,\mathrm{m}$ height and RG rainfall rate R_{RG}:

$$C_{\mathrm{MRR}} = \overline{\mathrm{dB}R_{\mathrm{MRR}} - \mathrm{dB}R_{\mathrm{RG}}} \tag{7}$$

Table 3. Micro rain radar (MRR) logarithmic calibration factor C_{MRR}

MRR	Period	C_{MRR}	$\sigma_{C_{\mathrm{MRR}}}$
WMH	01.01.2013 - 09.11.2014	$-3.06\,\mathrm{dB}$	$\pm 1.22\,\mathrm{dB}$
	10.11.2014 - 20.06.2015	$0.87\,\mathrm{dB}$	$\pm 1.06\,\mathrm{dB}$
	21.06.2015 - 31.08.2021	$-1.61\,\mathrm{dB}$	$\pm 1.34\,\mathrm{dB}$
BBG	06.12.2017 - 31.08.2021	$-1.37\,\mathrm{dB}$	$\pm 1.49\,\mathrm{dB}$

225 with $\mathrm{dB}R = 10 \cdot \log(R)$. Wind-induced losses of R_{RG} were corrected using the wind speed of a wind sensor (Rubel and Hantel, 1999). Rainfall rates at temperatures below $5\,^{\circ}\mathrm{C}$ were not included to constrain the adjustment on the liquid phase. The MRR variables, e.g. Z_{MRR} and R_{MRR}, are adjusted at all 31 height levels with C_{MRR} in logarithmic or linear units, respectively. C_{MRR} is ~~sufficient~~ sufficiently stable for periods covering multiple months (Table 3) and changes were a result of maintenance.

The adjusted MRR WMH radar reflectivity is used to calibrate the LAWR radar reflectivity (Fig. 3 a), yielding a consistent 230 calibration, because the MRR WMH and ~~LAWR HHG~~ the LAWR are measuring simultaneously since May 2013. The distance between the MRR WMH and ~~LAWR HHG~~ the LAWR is 10.07 km. At the MRR WMH location, the LAWR ~~HHG~~ mean radar beam height is between $680\,\mathrm{m}$ and $1170\,\mathrm{m}$ over the years, due to changes in radar alignment (Sect. 3.2), and the radar beam width is $490\,\mathrm{m}$ covering a maximum of 14 range bins of the MRR (Fig. 3 b). For radar beam elevation angles above 4.2°, the radar beam exceeds the maximal MRR range gate partly, increasing the volume mismatch. The profile of Z_{MRR} is averaged 235 within ~~LAWR HHG~~ the LAWR radar beam using a Gaussian weighting function, with its maximum at the beam centre (Fig. 3 b). Z_{MRR} at $10\,\mathrm{s}$ temporal resolution are averaged to the matching $30\,\mathrm{s}$ LAWR resolution. Following Lengfeld et al. (2014), the calibration coefficient c_{LAWR} is derived with

$$c_{\mathrm{LAWR}} = 10^{0.1 \cdot (\mathrm{dB}Z_{\mathrm{LAWR}} - \mathrm{dB}Z_{\mathrm{MRR}})} \tag{8}$$

with $\mathrm{dB}Z_{\mathrm{MRR}}$ ~~is~~ being the radar reflectivity of MRR WMH and $\mathrm{dB}Z_{\mathrm{LAWR}}$ ~~is~~ being the radar reflectivity of ~~LAWR HHG~~ the 240 LAWR. c_{LAWR} is calculated for radar reflectivities $\geq 10\,\mathrm{dBZ}$ and $< 60\,\mathrm{dBZ}$. The calibration is constrained on the liquid phase, hence radar reflectivities affected by the melting layer and ice phase are not taken into account. Therefore, $0\,^{\circ}\mathrm{C}$ isotherm level is estimated using a constant wet adiabatic lapse rate of $5.5\,\mathrm{K\,km^{-1}}$ and the $2\,\mathrm{m}$-temperature measured at the MRR WMH site. Radar reflectivities below the $0\,^{\circ}\mathrm{C}$ isotherm level are used for calibration only. The calibrated radar reflectivity factor Z'_{LAWR} is derived from

$$245 \quad Z'_{\mathrm{LAWR}} = \frac{Z_{\mathrm{LAWR}}}{c_{\mathrm{LAWR}}}. \tag{9}$$

with the measured radar reflectivity Z. The calibration results in 13 calibration periods with c_{LAWR} ~~is~~ between ≈ 0.03 and ≈ 4.4 (Table 4), due to maintenance including technical changes or drifts in signal intensity. The calibrated radar reflectivity $\mathrm{dB}Z'_{\mathrm{LAWR}}$ is provided as level 1 data set (Burgemeister et al., 2024).

Table 4. Calibration parameters for the ~~X-band radar (~~LAWR~~) HHG~~ with the calibration coefficient c_{LAWR} (Eq. (8)), the mean bias, the root-mean-square error (RMSE), the sample size (n), and the Pearson correlation coefficient (r). Measurements are only available in these periods.

Period	c_{LAWR}	bias (dB)	RMSE (dB)	n	r
27.05.2013 - 20.02.2014	0.062068	−12.07	12.47	7278	0.75
12.07.2014 - 23.09.2014	0.080461	−10.94	12.13	2061	0.50
23.09.2014 - 15.01.2015	0.026707	−15.73	16.16	728	0.43
17.01.2015 - 09.06.2015	3.865626	5.87	6.60	3362	0.84
09.06.2015 - 02.05.2016	2.053080	3.12	4.33	26017	0.87
02.05.2016 - 09.03.2017	1.761379	2.46	3.92	15710	0.87
22.03.2017 - 15.05.2017	0.342959	−4.52	5.78	1898	0.78
16.05.2017 - 05.07.2017	0.097155	−10.13	10.72	5658	0.72
05.07.2017 - 01.02.2018	0.971519	−0.13	3.12	25567	0.83
01.02.2018 - 18.04.2018	0.306367	−5.14	5.96	1603	0.86
20.04.2018 - 07.03.2020	2.837791	4.53	5.49	36207	0.86
25.04.2020 - 09.06.2020	4.409915	6.44	7.33	851	0.86
03.07.2020 - 11.08.2021	0.237148	−6.25	7.11	14379	0.79

3.5 Correct attenuation

Rain-induced attenuation leads at X-band frequencies to strongly underestimated radar reflectivities and thus rainfall rate estimates. The radar reflectivity factor Z' at range r suffers from attenuation integrated over the path,

$$Z'(r) = Z(r) - 2 \int_0^r k(s)\,\mathrm{d}s, \tag{10}$$

where $Z(r)$ is the unattenuated radar reflectivity factor at range r and $k(s)$ is the specific attenuation of each range bin. The second term in Eq. (10) is known as the two-way path-integrated attenuation (PIA). Overeem et al. (2021) suggests the modified Kraemer (MK) approach (Jacobi and Heistermann, 2016) to correct the attenuation for single-polarized radars. The MK approach is a forward gate-by-gate attenuation correction Hitschfeld and Bordan (1954) based on an iterative scheme ~~(Krämer and Verworn, 2008) of Hitschfeld and Bordan (1954)~~ to improve empirical parameters of a relationship between k and Z (Krämer and Verworn, 2008) including additional constraints of the PIA and Z (Jacobi and Heistermann, 2016). The attenuation k used in Eq. (10) is estimated from Z in $\mathrm{mm^6\,m^{-3}}$ using the power-law relation

$$k = \alpha Z^{\beta}, \tag{11}$$

with empirical parameters α and β. These empirical parameters are determined iteratively during the attenuation correction procedure. For details of this technique, we refer to the literature (Jacobi and Heistermann, 2016; Overeem et al., 2021) and
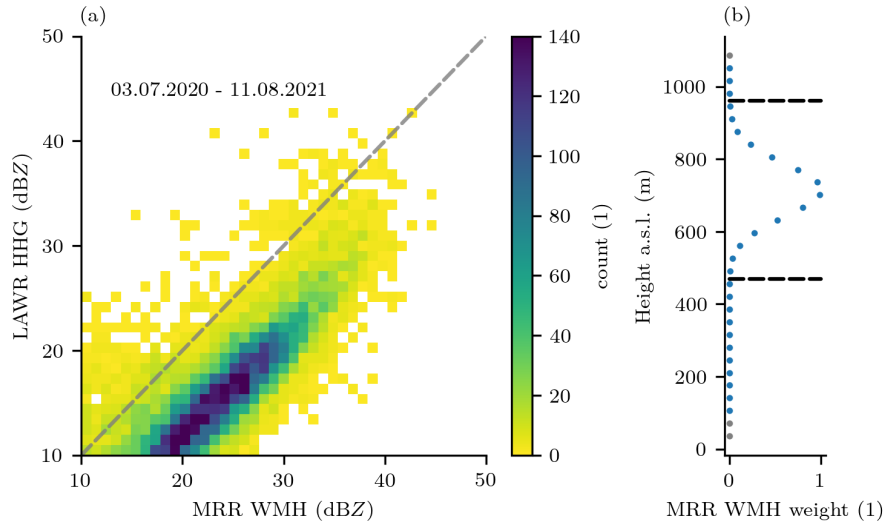
Figure 3. Calibration of ~~X-band radar~~ (LAWR ~~)~~ radar reflectivities using height averaged ~~micro rain radar~~ (MRR ~~)~~ ~~WMH~~ radar reflectivities. (a) Comparison of uncalibrated ~~X-band radar~~ (LAWR ~~)~~ radar reflectivities to calibrated radar reflectivities of the ~~micro rain radar~~ (MRR ~~)~~ WMH of the period 03.07.2020 to 11.08.2021 (Table 4). (b) Weights (dots) to average the MRR WMH radar reflectivity profile within the LAWR ~~HHG~~ beam (indicated by black dashed line) measuring at a beam elevation of $3.5°$.

document here only the specific settings of our implementation: The maximum allowed corrected reflectivity to assume a stable correction scheme is set to $59\,\mathrm{dBZ}$. The PIA is constrained by $10\,\mathrm{dB}$ (Delrieu et al., 1999) to avoid numerical instabilities.

265 The number of iterations for α is 100 and for β is 6. The limits of α and β are set to $\alpha_{\mathrm{min,\,max}} = [4.02 \cdot 10^{-5},\ 9.52 \cdot 10^{-5}]$ and $\beta_{\mathrm{min,\,max}} = [0.79,\ 0.90]$ (Figure 4). This valid range of α and β is in agreement with estimates of other k-Z relations at X-band (e.g. Delrieu et al., 1999; Berne and Uijlenhoet, 2006; van de Beek et al., 2010; Diederich et al., 2015; Delrieu et al., 2022).

However, these limits were not available from literature as Jacobi and Heistermann (2016) and Overeem et al. (2021) applied

270 the MK approach only at C-band frequencies. We applied the approach of Overeem et al. (2021) at X-band frequencies. The k-Z relation is estimated from multi-year MRR measurements (Fig. 4). The fit of the k-Z relation (Eq. (11)) results in ~~$\hat{\alpha} = 6.91$~~ $\hat{\alpha} = 6.91 \cdot 10^{-5}$ and $\hat{\beta} = 0.85$. The fit is applied only to $Z \geq 30\,\mathrm{dBZ}$ to stabilize the solution for relevant values of k affecting the attenuation correction. Overeem et al. (2021) ~~introduces~~ introduced the uncertainties of Eq. (11) based on the errors of k estimates, assuming that the uncertainties in $\log(\alpha)$ and β are independent and contributing equally to the total uncertainty in

275 $\log(k)$:

$$\varepsilon_{\log(\alpha)} = \frac{\log(k) - \log(\hat{\alpha} Z^{\hat{\beta}})}{2}, \tag{12}$$
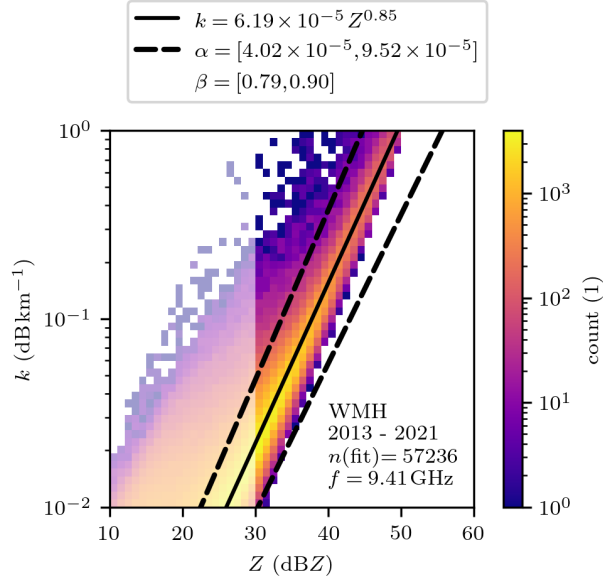
Figure 4. Relation between the specific attenuation k and the radar reflectivity $\mathrm{dB}Z$ estimated from micro rain radar measurements at $105\,\mathrm{m}$ height and $10\,\mathrm{s}$ temporal resolution. Only measurements at temperatures above $0\,^\circ\mathrm{C}$ are used to exclude ice phase. The radar variables are computed at the X-band frequency from measured drop size distributions with T-matrix calculations (Waterman, 1965) implemented by Leinonen (2014) using raindrop axis ratios from Brandes et al. (2002), a canting angle distribution with zero mean and 10° width, and the complex refractive index of water from Liebe et al. (1991) at a temperature of $15\,^\circ\mathrm{C}$. The power-law fit for the k-Z relation is based on measurements above $30\,\mathrm{dBZ}$ (~~dashed black line~~non shaded area) and is shown with a ~~red~~ black solid line, including uncertainties indicated as dashed ~~red~~ black line.

$$\varepsilon_\beta = \frac{\log(k) - \log(\hat{\alpha} Z^{\hat{\beta}})}{2\log(Z)}. \tag{13}$$

The uncertainties result in the aforementioned limits of the empirical parameters $\alpha_{\mathrm{min,\,max}} = \hat{\alpha}\exp(\pm 2\sigma_{\varepsilon_{\log(\alpha)}})$ and $\beta_{\mathrm{min,\,max}} =$
280 $\hat{\beta} \pm \sigma_{\varepsilon_\beta}$. The standard deviations are estimated from the difference between the 0.16 and 0.84 quantiles of ε (Overeem et al., 2021).

Finally, the MK approach is applied to the radar reflectivity from the level 1 data set, resulting in attenuation corrected radar reflectivity of the level 2 data set. Additionally, level 2 data set include the parameter pia_stability describing the stability of the attenuation correction for every time step. The parameter is 0 for a stable PIA estimate, 1 for a PIA $> 10\,\mathrm{dB}$, and 2 for a
285 numerical unstable PIA. The attenuation is not corrected if the PIA estimate is numerical unstable. Since the attenuation correction is based on the reflectivity, a prior successful calibration (Section 3.4) is mandatory for a stable attenuation correction. The attenuation correction algorithm can be easily applied using the python package wradlib (Heistermann et al., 2013).

3.6 Estimate rainfall rates

For use in meteorological or hydrological studies, quantitative precipitation estimates are of interest. The attenuation corrected radar reflectivity factor Z in $\mathrm{mm}^6\,\mathrm{m}^{-3}$ is converted to a rainfall rate R in $\mathrm{mm\,h}^{-1}$ by applying a power-law Z-R relation,

$$Z = a\,R^b, \tag{14}$$

where the multiplicative factor a and the exponent b are empirical constants. This study uses fixed parameters $a = 200$ and $b = 1.6$ proposed by Marshall et al. (1955), keeping in mind that Z and R depend on the drop size distribution, which varies geographically, with rainfall ~~intensity~~ rate, and time (e.g. Doviak et al., 1993; Villarini and Krajewski, 2010; Berne and Krajewski, 2013). However, the Marshall-Palmer Z-R relation is an appropriate representation of average rainfall conditions in this climate, as investigated with multi-year MRR drop size distributions in Hamburg (not shown) and by Holleman (2006); Kirsch et al. (2019). The coefficients of the Marshall-Palmer Z-R relation are commonly used for long-term studies in similar climate (e.g. Overeem et al., 2021; Imhoff et al., 2021). Polarimetric rain retrievals cannot be applied due to the lack of polarimetric measurements, but ~~benefit~~ would perform better compared to single radar reflectivity methodologies (e.g. Schleiss et al., 2020; Delrieu et al., 2022). The estimated rainfall rate R (Eq. (14)) in $\mathrm{mm\,h}^{-1}$ is provided as level 2 data set (Burgemeister et al., 2024).

3.7 Data sets and availability

The LAWR is measuring raw radar reflectivities since 27.05.2013 with a yearly data availability of up to $98\,\%$ (Table 5). Maintenance, radar errors or memory errors have reduced the data availability. The LAWR measurements are saved at the listed data levels following the data standard described by Lammert et al. (2018):

- The **raw radar data** is the direct radar output saved as hourly binary files.

- The **level 0 data** set includes the radar reflectivity $\mathrm{dB}Z$ and the standard deviation of the radar reflectivity factor of the averaged single pulses in hourly netCDF files.

- The **level 1 data** set includes the calibrated radar reflectivity $\mathrm{dB}Z$ (Sect. 3) in ~~hourly~~ daily netCDF files and is freely available (Burgemeister et al., 2024), facilitating studies on attenuation correction and the derivation of further weather radar products, e.g. an improved rainfall rate. Furthermore, new interpolation methods can be tested because interpolated values are tagged with a clutter mask.

- The **level 2 data** sets contains the attenuation corrected radar reflectivity $\mathrm{dB}Z$ and rainfall rate R in ~~hourly~~ daily netCDF files. R is provided as open data set (Burgemeister et al., 2024), facilitating refined studies on the spatial and temporal scale of precipitation and further hydrological research, e.g. input data for high-resolution modelling, in an urban area.

All data sets are gridded on the polar observation grid. Additionally, the level 2 data set includes the georeferenced grid information with the latitude, longitude, and height.

Table 5. LAWR data availability between the years 2013 and 2021

year	percentage of availability (%)
2013	57
2014	61
2015	97
2016	98
2017	93
2018	96
2019	98
2020	79
2021	61

4   Data quality

Several sources of radar-based errors were adjusted gradually (Sect. 3), aiming to improve the data quality of the radar re-
320   flectivity and, consequently, the rainfall rate estimate. This section outlines the performance of the multi-year X-band radar
observations and discusses open issues and limitations of the reanalysed data set.

Quantitatively, the reanalysed LAWR measurements are evaluated using MRR measurements at ~~common volumes~~matching
heights, following the same procedure as in Sect. 3.4 for the calibration. Therefore, the MRR radar reflectivity factor and rainfall
rate are averaged at height levels within the LAWR radar beam using a Gaussian weighting function~~, which is following the~~
325   ~~same procedure as in Sect. 3.4 for the calibration~~. The MRR's $10\,\mathrm{s}$ temporal resolution is averaged to the matching LAWR's
$30\,\mathrm{s}$ resolution. The comparison of measurements is constrained to the liquid phase, using the $2\,\mathrm{m}$-temperature and a constant
wet adiabatic lapse rate, which reduces effects from a bright band.

The LAWR attenuation-corrected radar reflectivity $\mathrm{dB}Z$ (level 2 data set) is on average $0.52\,\mathrm{dB}$ higher than the MRR
WMH reference (Fig. 5). The root-mean-square error (RMSE) equals to $3.93\,\mathrm{dB}$ and the reflectivities are highly correlated
330   with a Pearson correlation coefficient $r = 0.88$. The positive bias is a result of the performed calibration without attenuation
correction, because calibrated reflectivities are a prerequisite for stable attenuation correction (Sect. 3.5). Accordingly, all
scores improve, if only cases with moderate attenuation, below the $\mathrm{PIA} \leq 10\,\mathrm{dB}$ threshold, are considered: bias of $0.26\,\mathrm{dB}$, a
RMSE of $3.52\,\mathrm{dB}$, and $r = 0.89$. Just $8.5\,\%$ of the applied attenuation estimates are unstable with $10\,\mathrm{dB} < \mathrm{PIA} < 27.12\,\mathrm{dB}$.
These unstable attenuation estimates appear as a slight visible overestimation of the LAWR measurements at high reflectivities
335   ($\gtrsim 30\,\mathrm{dBZ}$) (Fig. 5), but these measurements are still usable with $r = 0.79$. In the case of a numerically unstable attenuation
estimate, radar reflectivities are not corrected (79 times; $0.03\,\%$). Note that only $19.7\,\%$ of the LAWR measurements (Fig. 5)
are interpolated. The scores depicted in Fig 5 do not change if these measurements are discarded. The independent reflectivity
measurements of the MRR BBG (not shown) confirm the data quality: bias of $-0.30\,\mathrm{dB}$, RMSE of $3.85\,\mathrm{dB}$, and $r = 0.88$.
Hence, the LAWR reflectivity is not biased in total.
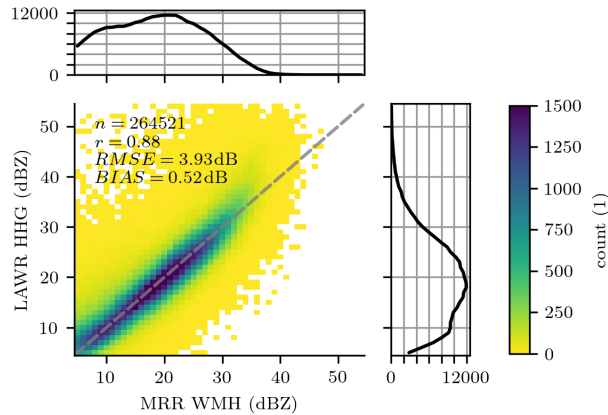
Figure 5. 2d distribution of radar reflectivities estimated from LAWR and MRR WMH based on drop size distributions at common volumes and a temporal resolution of $30\,\mathrm{s}$ restricted to $\mathrm{dB}Z$ between $4.5\mathrm{dBZ}$ and $59.5\mathrm{dBZ}$. The measurements are compared for the reanalysed data set covering the years 2013 to 2021.

340   The LAWR rainfall rate R (level 2 data set) is retrieved from the attenuation-corrected radar reflectivity using the Marshall-Palmer Z-R relation (Sect. 3.6). The LAWR rainfall rate is on average $0.42\,\mathrm{mm\,h^{-1}}$ lower than the reference (Fig. 6). The RMSE equals to $4.69\,\mathrm{mm\,h^{-1}}$. The Pearson correlation coefficient for the logarithmic rainfall rate $\mathrm{dB}R$ is $r = 0.74$. Since the reflectivities of LAWR and the MRRs are in good agreement, the comparison of the rainfall rates mainly investigates the performance of the Marshall-Palmer Z-R relation. The average underestimation of rainfall rates is in line with Kirsch

345   et al. (2019), who shows that the Marshall-Palmer Z-R relation underestimates rainfall accumulation derived from drop size distributions by between 6.3% and 17.4%. The error increases in cases of strong convective precipitation because raindrop size distributions start to deviate from Marshall-Palmer distributions for these cases (Schleiss et al., 2020).

    Although, the rainfall rate estimates can deviate for individual time steps, LAWR measurements ~~reproduces~~ reproduce the frequency distribution of rainfall rates as observed by the two MRRs very well (Fig. 7). In particular, the LAWR is able

350   to identify rainy time intervals. The overestimation of low rainfall rates $R < 0.2\,\mathrm{mm\,h^{-1}}$ is probably an issue of the MRR's attenuation correction. The decrease at the lower tail of the frequency distribution of MRR rainfall rate is only observable at high measurement levels (Fig. 8), where the uncertainty of the attenuation correction increases. At near-ground measurement levels, the rainfall rate frequency distributions of MRR and LAWR are equal at low rainfall rates of $R < 1\,\mathrm{mm\,h^{-1}}$ and high rainfall rates of $R > 10\,\mathrm{mm\,h^{-1}}$. In hydrological applications, accurate rainfall estimates are of interest at ground level (Thorndahl

355   et al., 2017). The vertical variability of rainfall properties, e.g. due to evaporation or wind drift, may limit the application of the provided LAWR rainfall rates at ground level (Villarini and Krajewski, 2010). The evaluation of LAWR rainfall rate at beam height with the MRR WMH measurement at $105\,\mathrm{m}$ shows differences in the frequency distribution between $2\,\mathrm{mm\,h^{-1}}$ and $10\,\mathrm{mm\,h^{-1}}$ as a possible result of vertical rainfall variability (Fig. 8). Nevertheless, the LAWR measurements yield reliable rainfall rate estimates at beam height and sub-minute temporal scale.
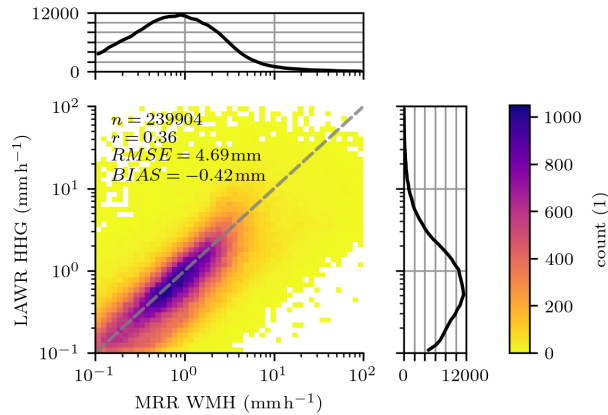
Figure 6. 2d distribution of rainfall rates estimated from LAWR using a standard Z-R-relation and MRR WMH based on drop size distributions at a temporal resolution of $30\,\text{s}$ and for R is between $0.1\,\text{mm}\,\text{h}^{-1}$ and $100\,\text{mm}\,\text{h}^{-1}$.
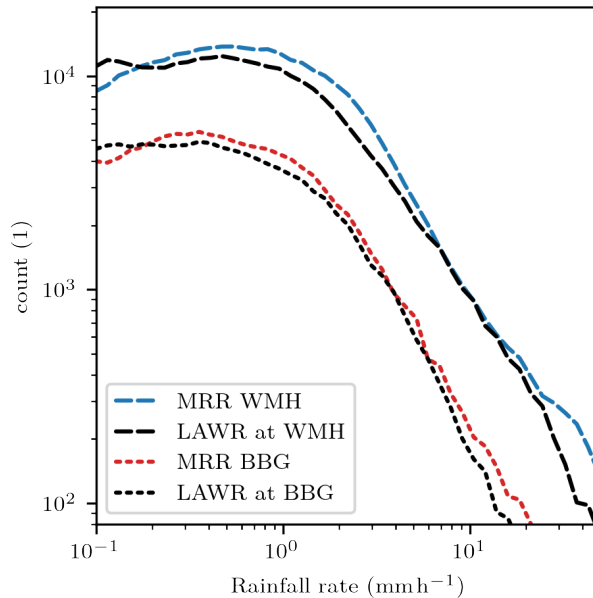
Figure 7. Frequency distribution of rainfall rates estimated from LAWR using a Z-R-relation and MRR WMH and MRR BBG based on drop size distributions averaged at beam height at a temporal resolution of $30\,\text{s}$.

360   Qualitatively, the LAWR measurements provide ~~continuos~~ continuous spatio-temporal rainfall patterns. The LAWR resolved a characteristic circular hook echo in the $30\,\text{s}$ average rainfall rate, demonstrating a rotating rainfall circulation around a tornado (Fig. 9), as discussed by Hoffmann et al. (2018). The provided LAWR rainfall rate R (level 2 data set) shows less remaining clutter compared to the processed rainfall rate by Hoffmann et al. (2018). Differences between the rainfall rates occur due to
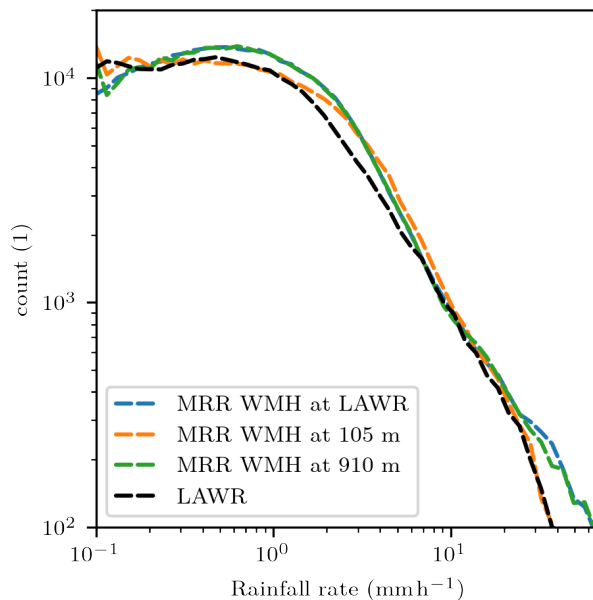
Figure 8. Frequency distribution of rainfall rates estimated from LAWR using a Z-R-relation and MRR WMH based on drop size distributions at a temporal resolution of $30\,\mathrm{s}$ at different height levels and averaged at beam height.

differences in processing steps, e.g. clutter removal, attenuation correction, and the applied Z-R relationship. However, the qualitative statements remain the same. The hook echo is clearly visible for eight minutes, in 16 measurement time steps, accordingly. The German nationwide C-band radars, measuring with $5\,\mathrm{min}$ temporal and $250\,\mathrm{m}$ range resolution, show the general rainfall pattern but the hook echo only at one measurement time step. As a consequence, this event demonstrates that the LAWR, with its refined spatio-temporal resolution compared to coarser resolved C-band radars, is capable to resolve rainfall patterns with a short duration and relevant gradients at hectometre spatial scale.

~~Fine-scale~~ The fine-scale structures in rainfall patterns ~~decrease with accumulationtime, nevertheless, within the measurement area remain differences in~~ are smoothed by temporal accumulation; nevertheless, spatial differences are still visible in the three-month ~~total precipitation~~ rainfall accumulation (Fig. 10). The rainfall pattern is mainly driven by convective summer rainfall events. The rainfall accumulations reveal long-term measurement errors, i.a. remaining clutter close to the radar and three spikes. First, range gates close to the radar are still affected by clutter after the application of correction algorithms, resulting in a small circle of high rainfall accumulations. Approximately $500\,\mathrm{m}$ around the radar location, the first eight of 333 range gates, show the overestimated total precipitation. Second, three spikes are characterized by an underestimation of total precipitation affecting multiple azimuth angles over the whole range. Two spikes in the north-east of the radar are a result of metal poles installed at a few meters distance to the radar on the rooftop, reaching in the radar beam. A third spike is in the south of the radar as a result of Hamburg's television tower, which is located in $550\,\mathrm{m}$ distance to the radar. The spikes affect the azimuth angles roughly from $19°$ to $30°$, $32°$ to $42°$, and $166°$ to $171°$. Note, measurements within these azimuth sectors, comprising
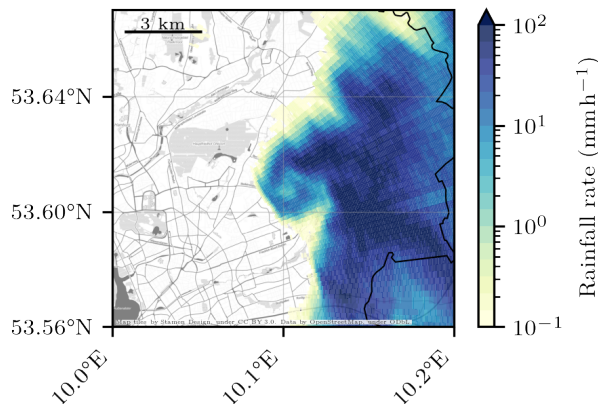
Figure 9. Rainfall pattern during a Tornado event on 07.06.2016 at 16:20:30 UTC. The rainfall rate is shown for a north-eastern section of the measurement domain in Hamburg. An animation of this event is provided in the supplements.

25 of 360 azimuth angles, need to be corrected for beam blockage or rejected for studies using this radar rainfall estimate. Without these errors, the three-month total precipitation is in general not affected by clutter, noise or attenuation (Fig. 10). The total precipitation was on average $168.0\,\mathrm{mm}$ and the median is $165.1\,\mathrm{mm}$ within the measurement domain in summer 2019. The three-month rainfall accumulations are spatially variable in Hamburg, with a minimum of $111.6\,\mathrm{mm}$ and a maximum of

385   $271.3\,\mathrm{mm}$. Note, the rainfall patterns at ground can deviate in comparison to the measured rainfall pattern at beam height because of vertical rainfall variability (Villarini and Krajewski, 2010). Four rain gauges measured $194.8\,\mathrm{mm}$ (north), $127.6\,\mathrm{mm}$ (east), $134.0\,\mathrm{mm}$ (south), and $172.9\,\mathrm{mm}$ (west) during the three months (Fig. 10). The absolute biases between the radar rainfall accumulations and rain gauge measurements range from $1.9\,\mathrm{mm}$ to $20.1\,\mathrm{mm}$. In general, the rain gauge observations are in agreement with the estimated radar rainfall accumulations during this measurement period. Consequently, the LAWR provides

390   reliable rainfall estimates with accumulation times from $30\,\mathrm{s}$ to multiple months.

    All in all, the reanalysed, multi-year LAWR measurements give insight in the spatio-temporal structure of rainfall at $30\,\mathrm{s}$ temporal and hectometre spatial scale in an urban area. The LAWR and MRRs are continuously in good agreement. The reanalysed radar reflectivities and rainfall rates can be used for meteorological and hydrological studies, considering the following limitations:

395   – The LAWR data set is constrained to the liquid phase.

    – The attenuation correction can be unstable and, thus, radar reflectivities can be overestimated. In rare cases, radar reflectivities are not corrected for a numerical unstable attenuation correction.

    – Differences between the LAWR measurements at beam height and ground observations are a result of vertical variability of rainfall due to wind advection and evaporation of rainfall. Variations between measurement devices arise due to

400   differences in measurement principle and volume mismatches.
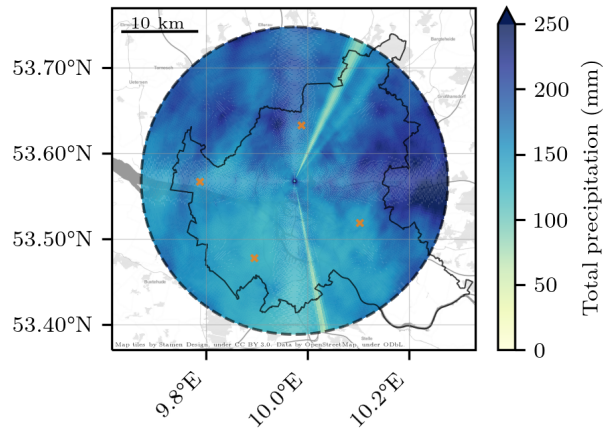
Figure 10. Three-month total precipitation measured by the LAWR during June, July, and August 2019. The radar estimates at four rain gauge locations (orange crosses) are $174.7\,\mathrm{mm}$ (north), $146.7\,\mathrm{mm}$ (east), $132.1\,\mathrm{mm}$ (south), and $157.1\,\mathrm{mm}$ (west).

- Remaining clutter and noise may overestimate single measurements. The first range gates can be superimposed by clutter.

- The LAWR is affected by beam blockage in three directions, resulting in three spikes in range within the measurements.

5 Conclusions

Firstly, this study describes quality-tested radar reflectivities and rainfall rate estimates with $30\,\mathrm{s}$ temporal and hectometre spatial resolution covering the years 2013 to 2021, that are provided as an ~~open-acess~~ open-access data set (Burgemeister et al., 2024). Secondly, this study proofs the multi-year performance of a local-area X-band weather radar (LAWR) despite the lack of polarization and Doppler information. The LAWR is deployed in combination with a vertically pointing micro rain radar (MRR) and rain gauge in the urban area of Hamburg, Germany, since 2013. The synergy of observations yield reliable LAWR measurements, confirmed by a second MRR.

Several sources of radar-based errors were adjusted gradually affecting the precipitation estimate, e.g. noise, alignment, non-meteorologial echoes, radar calibration, and attenuation. The manually adjusted LAWR alignment was accurately determined, using the solar signal appearing in radar reflectivities during sunrise and sunset, facilitating comparisons with other measurement devices. The deployment of MRRs yields drop size distributions at LAWR beam height. The LAWR reflectivities are calibrated using MRR reflectivities at intersecting volumes. The subsequent calibration of the LAWR is mandatory, because of strongly biased measurement periods due to maintenance, shown by the MRR observations. After calibration, the attenuation correction method, the modified Kraemer (MK) approach, is applied. The MRR drop size distributions facilitate the adjustment of parameters based on the relationship between the radar reflectivity and specific attenuation to apply the MK approach at X-band frequencies. This study presents the adjusted parameters and indicates that the MK approach is a reliable attenuation correction method for single-polarized X-band radars, shown with a long-term data set as suggested by Jacobi

and Heistermann (2016). The LAWR rainfall rates were estimated from attenuation-corrected reflectivities using the Marshall-Palmer Z-R relationship. The MRR rainfall rates, estimated from drop size distributions, show an on average underestimation of the LAWR rainfall rates estimated. Nevertheless, the retrieved, multi-year LAWR radar reflectivities and rainfall rates are in good agreement with MRR measurements.

Several issues may limit the performance of the LAWR measurements. This study focuses on the liquid phase, hence solid or mixed-phase precipitation, which is for instance dominant during the winter months, introduces errors within the provided data set, e.g. overestimated radar reflectivities due to the melting layer (Villarini and Krajewski, 2010). Remaining clutter and noise may remain within the reanalysed measurements. Rare unstable attenuation corrections overestimate the LAWR radar reflectivity. Affected radar reflectivities are labelled within the data set. Furthermore, LAWR measurements at beam height can differ from ground observations as a result of vertical rainfall variability due to wind drift and evaporation of rainfall, limiting the application of LAWR rainfall rates at ground level. The largest errors in ~~rain~~ rainfall rate estimates at individual time steps arise from inherent uncertainties of the Z-R relation, but they do not cause systematic deviation. The frequency distribution of ~~rain~~ rainfall rates is very well reproduced. Variations between measurement devices arise due to differences in measurement principles and volume mismatches. The assessment of the LAWR alignment identified measurement periods with beam elevation angles up to $6.1°$. A high beam elevation angle leads to, inter alia, partial overshooting of MRR measurement volumes, which is a problem of measurement design. The measurement design can be optimized by using lower LAWR beam elevation angles, e.g. $3.5°$, or a coarser MRR range resolution, e.g. $50\,\mathrm{m}$. In future, the issue of overshooting will be avoided, by using lower beam elevation angles, adding the benefit of measurements at lower altitudes. Measurements at lower beam elevation angles than $3°$ are not recommended, because the LAWR beam elevation setting is a compromise between measurement altitude and the occurrence of clutter signals. Note, MRR measurements also need quality control (Reinoso-Rondinel and Schleiss, 2021).

This multi-year urban radar rainfall data set is groundwork for further meteorological and hydrological research and is actively used in different meteorological studies ~~(e.g. Kirsch et al., 2022; ?; Ferner et al., 2022)~~(e.g. Kirsch et al., 2022; Schmitt et al., 2023;). Prospective research may investigate conditional and event-based errors in the multi-year LAWR measurements to quantify limitations of the LAWR. By including comparisons from the LAWR to additional independent sensors, the added value of the spatio-temporal information from low-cost, local-area X-band radars can be investigated. For hydrological research, LAWR rainfall rates should be evaluated with measurements at ground. Future urban precipitation studies will be improved by the extension of networked observations with a second X-band weather radar site and additional micro rain radars in Hamburg, measuring since the beginning of 2021.

6 Code and data availability

The pylawr python package (Burgemeister et al., 2023) provides useful tools to load, process, and plot the LAWR data and was used to process the provided data sets. The LAWR HHG data set of rainfall rates (level 2) and radar reflectivities (level 1) is available at WDCC: https://doi.org/10.26050/WDCC/LAWR_UHH_HHG_v2 (Burgemeister et al., 2024). Further LAWR

HHG observational data sets at different processing levels and MRR observations are available upon request. We strongly encourage anyone using the data set to be in contact with the authors.

455 *Author contributions.* All authors conceptualised the project and reviewed the draft. FB planned and processed the data sets, performed the evaluation, wrote and revised the draf. FB and MC maintained the X-band radar. FB and FA edited the draft. MC and FA conceptualised and implemented the measurement network.

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