Answers to the reviewers:

ESSD-2023-300 Data description paper

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

We thank the editor and the two anonymous reviewers for the time and effort they invested in critically reviewing our manuscript and data set. Please find answers (in blue) to your very helpful comments and suggestions below.

Answers to reviewer 1

The authors have compiled quite an impressive time series of a X-band weather radar in Hamburg with a high sptio-temporal resolution which fits the scope of ESSD well. They describe the need for such a dataset for applications in meteorological and hydrological applications and put their dataset in perspective to studies using such data. The description of the radar is exhaustive. They provide detailed information on the removal of noise, the alignment of the radar, clutter removal, attenuation correction, and rainfall retrieval. Finally, they list the use cases of the data and point out potential limitations. The overall quality of the manuscript and its figure is high, albeit in some cases more precise information could be given and the abstract would benefit from a major revision. The dataset itself is already at a good level, but user-friendliness could be further increased by added cf compliances, a reduction of the number of files, and the removal of numerical instability in the time dimension. The biggest issue is that WDCC requires a login and tracks downloads which is not compliant with ESSDs policy. After solving these issues I'd recommend the publication of this manuscript.

General comments on data

1) Data are under restricted access: WDCC requires a login and downloading persons are tracked. This does not comply with ESSDs policy.

This issue has been clarified by the topical editor and the WDCC.

2) Downloading more than one single data file was not possible for me. I could neither download a part of the dataset via the interface nor a complete monthly file.

This issue has been clarified by the topical editor and the WDCC.

3) Having files stored as daily or even monthly files would reduce the amount of files drastically. In the cases of maintenance, you could split the daily file into two to avoid adding the dim time to additional variables.

We will provide daily files and follow your suggestion to split the daily file into two in cases of maintenance. Monthly files are too large for users interested in sub-daily weather events, e.g. the tornado example (Hoffmann et al., 2018), cold pool events (Kirsch et al., 2022), single thunderstorm or strong precipitation events.

4) Data could be more cf compliant as the editor already pointed out in his assessment. In the individual files I could download I found numerical instabilities on the dimension time e.g. '2016-05-01T09:12:00.000000256', or '2016-05-01T09:02:29.999999744'. Rounding/reindexing the dim time to the full minute would remove this and errors e.g. in the selection or aggregation of data could be avoided.

We agree with the reviewers and the editor and will apply following changes to the data set to be more cf compliant. Originally, we followed the SAMD Product Standard (Standardized Atmospheric Measurement Data) by Lammert et al. (2018). We will follow the data levels of the SAMD Product Standard and the CF, and CfRadial conventions regarding the metadata.

(i) We will change the data type (*double* to **int64**) and the unit (*days since 1970-01-01* to **seconds since 1970-01-01**) of the time coordinate.

(ii) We will change the standard name of the variable azimuth from

- "*sensor_azimuth_angle*" (standard_name, CF-1.11) to
- "**sensor_to_target_azimuth_angle**" (standard_name, CfRadial).

(iii) We will change the long name/standard name of the variable range from

- ”*distance from sensor to center of each range gates along the line of sight*” (long_name, SAMD) to
- ”**line_of_sight_distance_from_instrument**” (standard_name, CfRadial).

(iv) We will change the long name/standard name of the variable ele from

- ”*sensor elevation angle*” (long_name, SAMD) to
- ”**sensor_to_target_elevation_angle**” (standard_name, CfRadial).

(v) We will add the integer variable **grid_mapping** with the attributes grid_mapping_name (”radar_lidar_radial_scan”), latitude_of_projection_origin, longitude_of_projection_origin and height_of_projection_origin, as suggested by the CfRadial conventions. Since the grid_mapping variable provides the same information as the variables lat_center, lon_center and zsl_center, we will remove them. We will add the attribute grid_mapping to the variable rr and dbz.

General comments on the manuscript

5) In general, the manuscript could be more precise. Try to avoid general statements like “more or less” (L200) or “in rare cases” (L371), and be more consistent with abbreviations (e.g. L211 “LAWR radar” vs L212 “LAWR HHG”). A bit picky from my side but still improving consistency is settling on either “rain rate” or “rainfall rate” (“rainfall intensity” is also used once).

We will be more precise, but also want a text that is easy to read. We will be more consistent with abbreviations and variable names.

(i) ”more or less” (L200): We removed this statement, please refer to the answer to comment 22 of reviewer 1.

(ii) “in rare cases” (L371): We will keep this general statement, but will provide exact details. Please refer to the answer to comment 8 of reviewer 1.

(iii) Thank you for this comment. We will change ”LAWR HHG” to ”LAWR” in Lines 212, 213, 216, 221, the description of Table 4, and the description of Fig. 3 because this study uses only one LAWR. However, we will keep ”LAWR HHG” in Sections 2 and 6 because there the specific name of the radar location is relevant. The name of this radar location can be used in further studies using a second radar. Likewise, we will keep ”LAWR radar reflectivities” because in these cases ”LAWR” refers to the measurement device and ”radar” to the variable ”radar reflectivities”.

(iv) Thank you for finding these inconsistencies. We will change ”rain rate” to ”rainfall rate” in Lines 54, 405, and 406. We will change ”rainfall intensity” to ”rainfall rate” in Line 274.

6) L1-9 This part of the abstract is not well-structured and somewhat imprecise. It is unclear what is part of the manuscript and what is part of previous studies and only after reading the respective sections in the manuscript it becomes clear which parts are done here. Please restructure the abstract. You could start with the second part (L.10-15), which is more concise, and expand it to include all sections included in the manuscript.

We will revise our abstract:
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 made available for a period of more than eight years.
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-meteorologial echoes, radar calibration, and attenuation. The deployment of additional vertically pointing micro rain radars yields drop size distributions at the radar beam height, which reduces errors effectively concerning the radar calibration and attenuation correction, and monitors the radar data quality. A statistical evaluation revealed that X-band radar reflectivities and rainfall rates are in very good agreement with the micro rain radar measurements. Moreover, the 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 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.

7) L133 A table or graphic describing the number/percentage of clutter points each filter removed, and hence having an estimate on the number of measured vs interpolated pixel values could add more perspective on the importance of the clutter filters and the quality of the raw LAWR observations.

Describing each clutter filter's general impact on the entire dataset proves to be challenging. A quantitative evaluation of the clutter filters is only reasonable for periods with rainfall events, excluding solid-phase measurements. The exact number of clutter points removed by each filter isn't included in the dataset because this increases the data size by a factor of four. However, all interpolated values are tagged with a clutter mask, which is a variable of the data set (Line 290). Therefore, clutter values can be identified. In Fig. 5, comparing the LAWR and MRR WMH radar reflectivity, 19.7 % of the shown values are interpolated pixels. In total, 12.6 % of the values at this location, which were above 4.5 dBZ before clutter removal, are tagged as clutter values, emphasizing the relevance of clutter filters even in non-precipitation and precipitation scenarios. Note, the clutter frequency varies by location in the measurement area.
For a comprehensive understanding of the clutter filter performance, we focus on May, June, July, August, and September 2019 data. We focus on radar reflectivities above 4.5 dBZ before clutter correction to demonstrate the effective clutter removal. On average 26.3 % of all values are effectively identified as clutter by the filter algorithms (Fig. 1; see below). 66.1 % of all clutter values are identified by the TDBZ filter. 25.7 % of all clutter values are identified by the SPIN filter. 3.1 % and 0.4 % of all clutter values are identified by the two spike filters. 1.0 % and 1.4 % of all values are identified by the two ring filters. 14.0 %, 19.3 %, 28.1 %, 30.6 % and 31.5 % of all clutter values are identified by the five speckle filters. Without removing the static clutter field 54.9 % (instead of 26.3 %) of all values are identified as clutter by the filter algorithms, which demonstrates the importance of the static clutter removal.
Figures 9 and 10 of the manuscript present case studies illustrating the successful clutter removal and interpolation. To give a perspective on the importance of the implemented clutter filters, we will add a paragraph to Section 3.3 in Line 193 and two sentences to Section 4 in Line 313, because this regards to the topic of data quality:

- *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 %)*

- *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.*

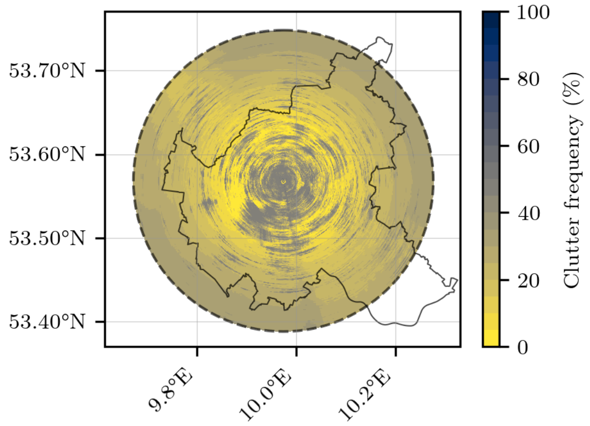

Figure 1: Effective clutter frequency in LAWR observations from May to September 2019.

8) L231 Correct attenuation. Similar to a quantitative estimate of clutter you can also provide estimates of stable and unstable attenuation correct in section 3.5. This can then be used e.g. in L371 to give a number instead of the expression "in rare cases".

We agree that the expression "in rare cases" is not precise, therefore we will provide an exact statement in Section 4, because this regards to the topic of data quality. A quantitative evaluation of the attenuation correction is only reasonable for cases constrained to the liquid phase. In Section 4, we outline the performance of the attenuation correction. In comparison between the LAWR and MRR radar reflectivity, "[...] 8.5 % of the applied attenuation estimates are unstable with 10 dB < PIA < 27.12 dB" (Line 311). In 79 cases (0.03 %), radar reflectivities are not corrected because of a numerical unstable attenuation correction. We will keep the statement "in rare cases" in Line 371 for readability but add a sentence to section 4 in Line 313:
In the case of a numerically unstable attenuation estimate, radar reflectivities are not corrected (79 times; 0.03 %).

9) Fig. 4, 5, and 6 You could consider using a colormap that has more variation for the colorbar, e.g. viridis or turbo

Thank you for this comment. We will include the figures 4, 5, and 6 with new colormaps (as shown below). Additionally, we replace the colormap of Fig. 3 similar to Fig. 4 to be consistent. The description of Fig. 3 will change to be more consistent with abbreviations (comment 5 of reviewer 1). The description of Fig. 4 will change to update the color of the lines and to introduce the shaded area. The description of the figures 5 and 6 will be unchanged.

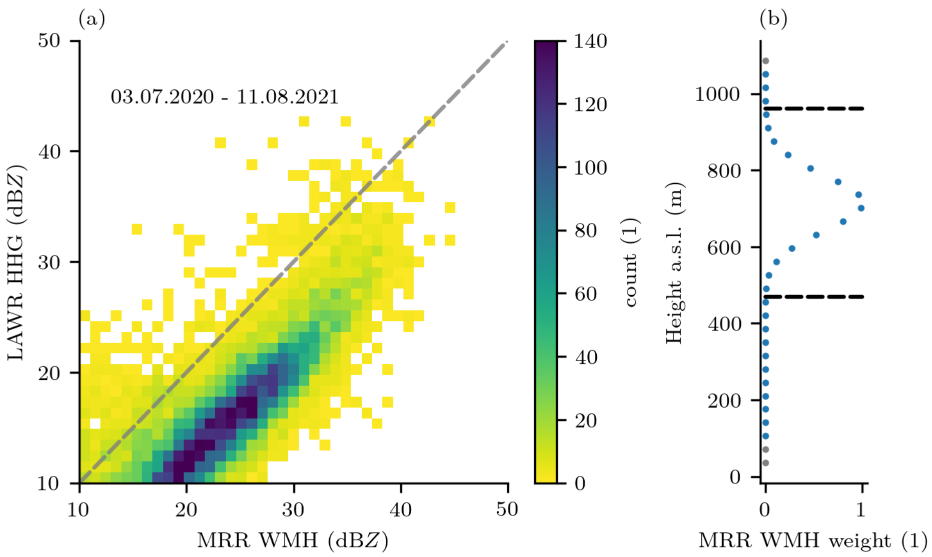

Figure 3: *Calibration of LAWR radar reflectivities using height averaged MRR radar reflectivities. (a) Comparison of uncalibrated LAWR radar reflectivities to calibrated radar reflectivities of the MRR WMH of the period 03.07.2020 to 11.08.2021 (Table 4). (b) Weights (dots) to average the MRR WMH radar reflectivity profile within the LAWR beam (indicated by black dashed line) measuring at a beam elevation of* $3.5°$.

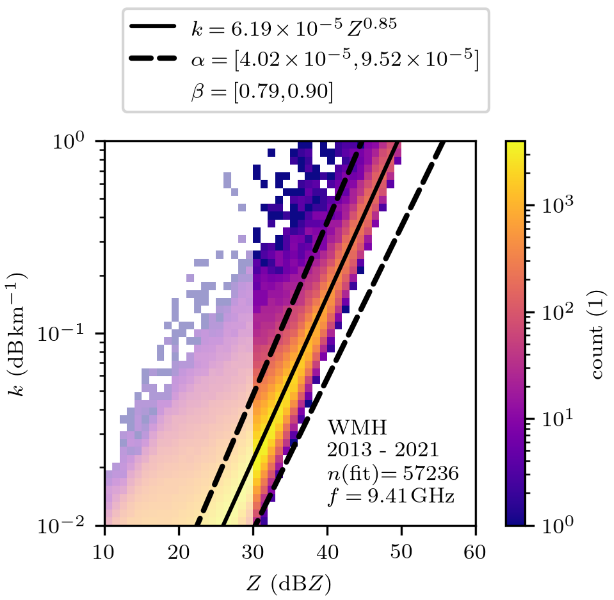

Figure 4: *Relation between the specific attenuation k and the radar reflectivity* dBZ *estimated from micro rain radar measurements at* 105 m *height and* 10 s *temporal resolution. Only measurements at temperatures above* $0\,°C$ *are used to exclude ice phase. The radar variables are computed at the 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* $15\,°C$. *The power-law fit for the k-Z relation is based on measurements above* 30 dBZ *(non shaded area) and is shown with a black solid line, including uncertainties indicated as dashed black line.*

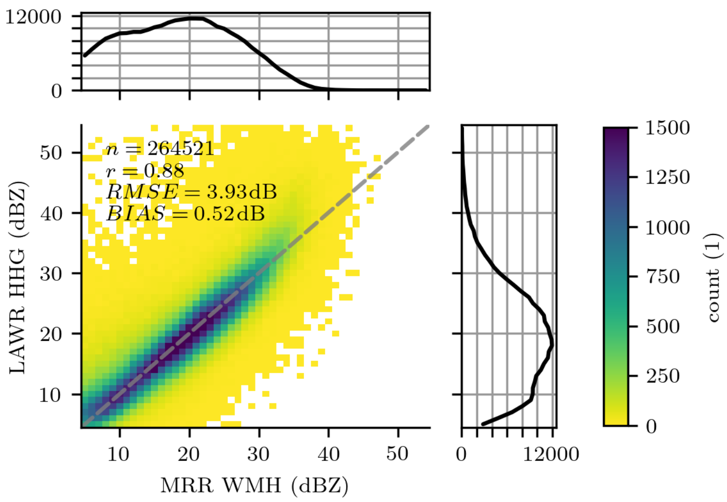

Figure 5: *[Figure description will be unchanged.]*

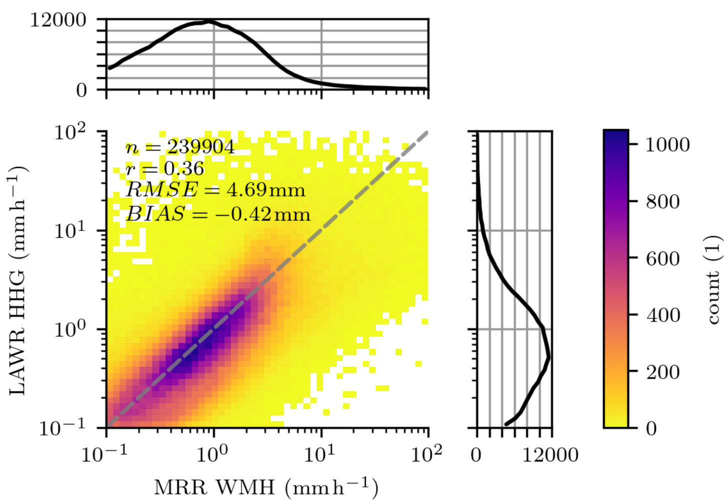

Figure 6: *[Figure description will be unchanged.]*

10) Fig. 9 You could add an animation of the event as an animated gif into the supplements of the manuscript.

We like the idea and will provide an animation of the event in the supplements of the manuscript. The animation will show the rainfall pattern in the north-eastern section of the measurement domain in Hamburg between 16:10:00 UTC and 16:40:00 UTC. We will add the sentence "*An animation of this event is provided in the supplements.*" to the description of Figure 9.

11) Table 4 It is not entirely clear to me if the days if all "rare days" of maintenance are listed as logged in Table 4. If yes, please indicate that the days between periods here are the maintenance days or otherwise provide this information elsewhere.

Changes of calibration parameters for the LAWR are a result of maintenance or drifts in signal intensity (Line 229). Missing days in the calibration parameter periods (Table 4) are days without data availability because the radar was down for maintenance or the measurements were clearly erroneous, e.g. strong signal drift or no measurement signal. We will add the sentence "*Measurements are only available in these periods.*" to the description of Table 4 to avoid miscommunications.

Technical comments on the manuscript

12) L2: "large domains and small temporal scales" is very unspecific, please modify the sentence

We will revise the abstract. For further details, refer to the answer of comment 6 of reviewer 1.

13) L14: change "will" to "can"

We will revise the abstract. For further details, refer to the answer of comment 6 of reviewer 1.

14) L22 Add "networks" after "Rain gauges provide" to make the sentence correct

Thank you, we will add this.

15) L67 "The measurements refine the observations of.." This and several similar statements e.g. in L.4 sound like the refinement is done operationally

You are right. We will revise the abstract (answer of comment 6). We will change the sentence in L67 to "*The measurements can refine the observations of the German nationwide C-band radars, and supplement and cover additional rain gauges.*"

16) L.121 "continues"

Thank you, we will change it.

17) L135 artificial: is this the correct wording?

You are right, we will change "artificial" to "erroneous".

18) L156 defines abbreviations TDBZ and SPIN on first use

We will define the abbreviation TDBZ on first use in Line 156. "SPIN" is not an abbreviation, therefore we can only refer to the reference on first use. Hubbert et al. (2009) defined the SPIN change as a reflectivity gradient change.

19) L156 be more precise by stating that you use two variants of a spike and two variants of a ring filter

This comment is similar to the comment 6 of reviewer 2. Consequently, we will remove the sentence "Since spikes and rings are of different length and width, two spike and two ring filters are applied to remove spikes and rings." in Line 183. As a replacement, we will add the sentence "*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.*" after the sentence in Line 156, which introduces the algorithms.

20) L182ff Please elaborate on the choice of N and W for the four filters

The choice of the parameters for the four filters were determined empirically by processing different case studies.

21) L194 Give some information on the Kriging method

We will give more information on the Kriging method. Missing values are interpolated using

the Kriging method (Cressie, 1993). In this case, the ordinary Kriging method is applied using a Gaussian kernel as covariance function with a temporal-constant length scale (5 km) and a constant stationary random noise. 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. The constant length scale was empirically found and can be improved by further studies. All interpolated values can be identified with a clutter mask (Line 290). We will add the two references and add two sentences:
Missing values are interpolated with ordinary Kriging (Cressie, 1993). The temporal-constant spatial covariance is modelled by a Gaussian semivariance with a length scale of 5 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.*

22) L200 more or less can be more precisely described by L214

This is correct. The MRR observes $\approx 1\,\%$ of the LAWR measurement volume size. However, the MRR sampling volume ($\approx 175000\,\mathrm{m}^3$) and height is superior to in situ measurements for comparisons with a different radar. We will remove the statement about the volume match and rephrase the sentence to:
The calibration and evaluation with MRR measurements has mainly three advantages: the same variable and the same measuring height are compared at sufficient large sampling volume sizes.

23) L221 being instead of is

Thank you, we will replace "is" with "being" both times.

24) L228 remove is

Thank you, we will remove "is".

25) L238 is the iterative scheme from Krämer and Verworn, 2008 or HHitschfeld and Bordan (1954)? This sentence is not entirely clear to me

The iterative scheme to optimize the parameters of the k-Z relation is from Krämer and Verworn (2008) and was modified by Jakobi and Heistermann (2016). We refer to Hitschfeld and Bordan (1954) for the basic foward gate-by-gate attenuation correction. We will rephrase the sentence to:
The MK approach is a forward gate-by-gate attenuation correction (Hitschfeld and Bordan, 1954) based on an iterative scheme 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).*

26) L254 change introduces to past tense

Thank you, we will change it.

27) L262 either write "from the level 1 data set" or "from level data"

Thank you, we will change it to "[...] from the level 1 data set, [...]".

28) L263 same as 262

Thank you, we will change it to "[...] of the level 2 data set".

29) L279 benefit might be the wrong word here, suggestion: “but would perform better compare to” could be

Thank you, we will change it.

30) L301 be more precise about common volumes

For the evaluation of the LAWR measurements using MRR measurements, we follow the same procedure as described in Sect. 3.4 for the calibration. The comparison at common volumes is demonstrated in Fig. 3b. The exact common volume depends on the elevation angle of the LAWR, as mentioned in Sect. 3.4. The exact volume match of the LAWR and MRR observations is small ($\approx 1\,\%$). However, for this application, the MRR measurements are superior to ground based observations of disdrometers because of the larger sampling volumes and the matching heights within the LAWR beam. To clarify the statement, we will rephrase the sentences in the lines 301 to 303 to refer to Sect. 3.4 at the beginning and use the word heights instead of volumes: ”*Quantitatively, the reanalysed LAWR measurements are evaluated using MRR measurements at 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.*”

31) L346 sentence structure

Thank you, we will rephrase this sentence to ”*The fine-scale structures in rainfall patterns are smoothed by temporal accumulation; nevertheless, spatial differences are still visible in the three-month rainfall accumulation (Fig. 10).*”

Answers to reviewer 2

The manuscript presents a new precipitation data set from high-resolution X-band radar measurements over the city of Hamburg between 2013 and 2021. It gives a good description of the radar itself and the data processing chain from raw reflectivity measurements to quality controlled rainfall estimates. An overview of previous studies that have already proven the usefulness of the dataset is also presented as well as recommendation for future applications.
The manuscript fits in the scope of ESSD, it is well written and clearly structured. The described data set is unique and allows for a variety of applications and studies in the field of small scale (extrem) precipitation and hydrology. However, accessing the data is a bit complicated and the large amount of files can be challenging. I recommend publishing the manuscript after taking the following suggestions and comments into account:

1) In the abstract there is a lot of information on former studies. In my opinion the abstract should be more about the current manuscript and less about other studies. Please consider rewriting the abstract with more focus on this manuscript.

We will revise the abstract. For further details, refer to the answer of comment 6 of reviewer 1.

2) In section 2.1 the author state that the elevation angle was adjusted several times during the measuring period. Does that influence the homogeneity of the data set in any kind of way?

The change in elevation angle of the LAWR influences the homogeneity of the data set regarding the altitude of the measurement. LAWR measurements at beam height differ from ground observations as a result of vertical rainfall variability due to wind drift and evaporation of rainfall. This effect increases with increasing altitude. However, this manuscript provides information on the exact elevation angle (Sect. 3.2). The MRR provides measurements at the beam height of the LAWR. With the known radar alignment and thus height of the measurements, we calibrated the LAWR measurements using the MRR, which increases the homogeneity of the data set.

3) Section 3.1: A flow chart or maybe some equations would be helpful to understand the method for the noise removal

We agree that a flow chart or some equations may support this section. Nevertheless, this algorithm is originally described by Lengfeld et al. (2014). Consequently, we want to describe the algorithm as short as possible and refer to Lengfeld et al. (2014). We created a flow chart (Fig. 2, see below), but think the description in the text is easier to understand. We will revise the sentence in Line 109 to align with the wording used in the following sentence:
If more than 10 % of the radar bins remain rain-free, the 10th percentile of the original $Z \cdot r^{-2}$ becomes the new noise level estimate; otherwise, the noise level from the prior time step is kept.

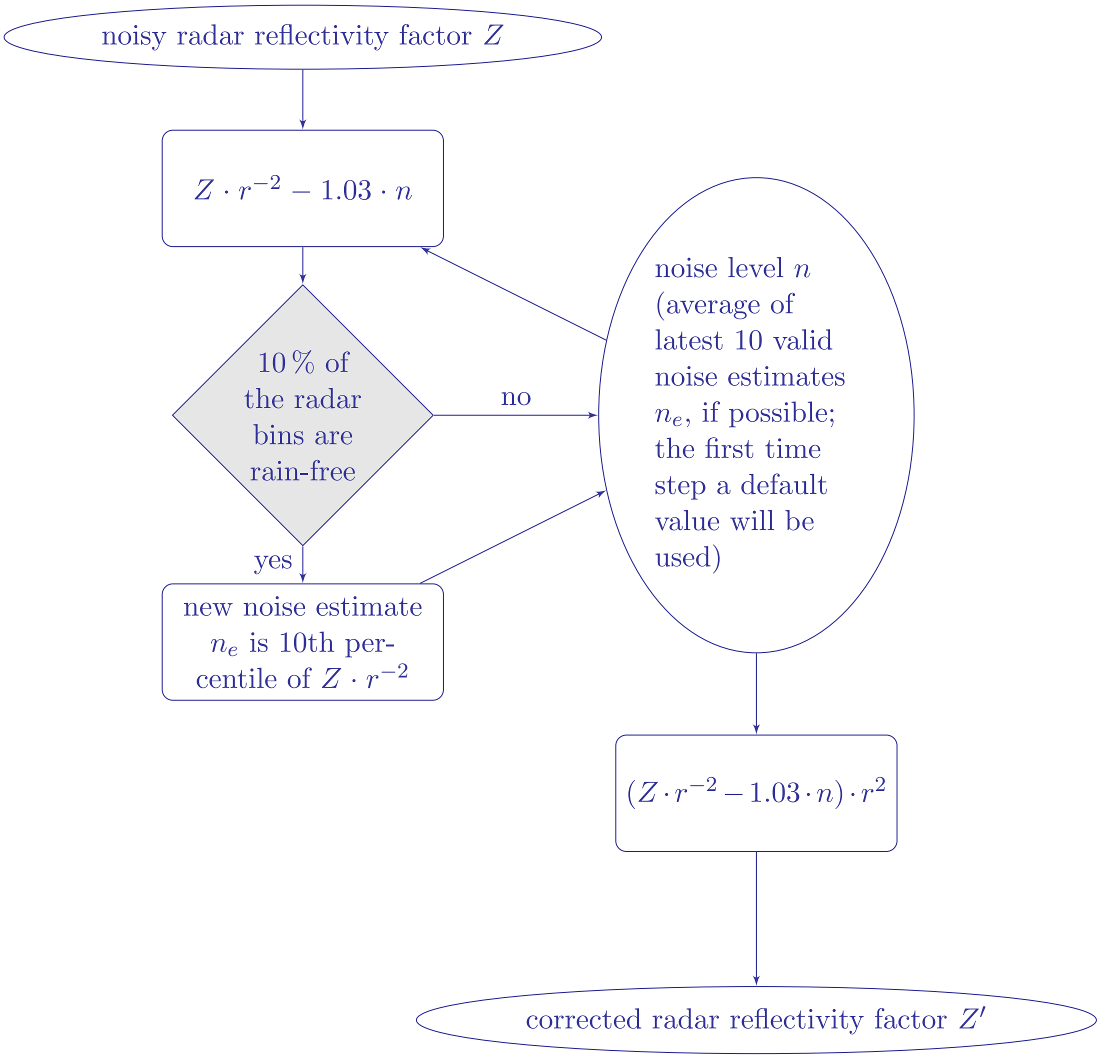

Figure 2: Sketch of a flow chart to describe the noise removal.

Minor comments

4) L.12: discuss à discusses

Thank you, we will change it.

5) L.121: continues à continuous

Thank you, we will change it.

6) L.183-184: The last sentence of the paragraph should be moved to beginning of the description of the ring and spike filters

This comment is similar to the comment 19 of reviewer 1. We will remove the sentence "Since spikes and rings are of different length and width, two spike and two ring filters are applied to remove spikes and rings." in Line 183. As a replacement, we will add the sentence "*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.*" after the sentence in Line 156, which introduces the algorithms.

7) L.209: Do the authors really many "e.g." or do they mean "i.e."?

We use the derived calibration factor to correct also additional MRR variables, like the liquid water content or the attenuated radar reflectivity, therefore we mean "e.g.".

8) L.210: sufficient à sufficiently

Thank you, we will change it.

9) L.252: Should'nt it be 6.91 x 10-5 for alpha instead of 6.91?

Thank you, we will change it.

10) Fig.4: Why is the upper boundary of the uncertainty outside of actual range of the measurements?

Thank you for this comment. This is a weakness of the approach of Overeem et al. (2021) to fit the limits of the MK approach (attenuation correction method), and can also be seen in Figure 4 of Overeem et al. (2021). The limits of the MK approach are based on the uncertainty of the empirical parameters α and β. As mentioned in the manuscript, the limits are derived from the standard deviation (approximated with quantiles) of $\varepsilon_{\log(\alpha)}$ (Eq. (12)) and ε_{β} (Eq. (13)). The distribution of these errors are positive skewed, therefore, the lower boundary $\alpha_{\min} = 4.02 \cdot 10^{-5}$ and $\beta_{\min} = 0.79$ is not well presenting the actual range of the measurements. This may lead to an underestimation of the actual attenuation. However, the MK approach starts the iteration with $\alpha_{\max}$ and $\beta_{\max}$. Additionally, we do not observe an underestimation of radar reflectivities in the comparison with the micro rain radar, shown in Section 4.

11) L.324: reproduces à reproduce

Thank you, we will change it.

12) L.336: continuos à continuous

Thank you, we will change it.

13) L.380: open-acess à open-access

Thank you, we will change it.

Dataset

14) Getting the data is bit difficult, because an account for WDCC is required. The users have to give information about their name, affiliation, which data they want to access and what they are planning to do with the data. It took about a day until my access was granted.

This issue has been clarified by the topical editor and the WDCC.

15) The large amount of files (one file per hour) is a bit overwhelming. I wasn't able to download a full month of data because of the size of the file. Downloading a part of the dataset was also quite a challenge. The user can choose a range of the dataset between "start record" and "end record". This works fine as long as the first number of "end record" is lower than the first number of "start record", e.g. start record = 1, end record = 9 works. But start record = 5 and end record = 20 gives an error, because end record starts with 2 which lower than 5. There seems to be a bug in the system.

To the topic of hourly data files: Please refer to the answer to comment 3 of reviewer 1.

To the topic of the download issue: We contacted the WDCC at DKRZ and reported the bug and they solved this issue. Thank you.

16) The netcdf-datafile itself is easy to handle, but could be more cf-compliant as the first reviewer and the editor already said.

We agree with the reviewers and the editor and will apply changes to the data set to be more cf compliant. Please refer to the answer to comment 4 of reviewer 1.

Additional changes

1) There is a typo in the unit in Line 31: 1 m instead of 1 min.

We will correct the unit.

References

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