

**Reply to the review of “Long-term Climatology of Vertical Profiles of Polarimetric Variables and Ice-microphysical Retrievals at X-band. Part I: Radar Calibration” by Tobias Scharbach and Silke Trömel, egusphere-2026-493.**

**Response to reviewer 2:**

**Thanks a lot for your time and the careful review of our paper. In the following, we address your comments point by point. You will find our responses highlighted in blue, together with your suggestions. Paragraphs or sentences we plan now to additionally include in the revised manuscript are underlined.**

**1.3 Introduction:**

- In your introduction, you also need to consider and discuss the following article: Figueras y ventura, 2012: <<https://rmets.onlinelibrary.wiley.com/doi/epdf/10.1002/qj.1934>> which contains relevant information similar to what you are doing"

Thank you, information from this paper should indeed be included. We suggest the following for the “Introduction“ section:

...“The latter exploits vertical scans, where raindrops appear nearly spherical to the radar, and is one of the most frequently used methods for accurate ZDR calibration. Similarly, ZDR is expected to be 0 dB when the radar is pointing towards the sun, due to the unpolarized nature of solar radiation in this direction. Monitoring the sun allows the detection potential receiver malfunctions or radar antenna misalignment (Holleman et al., 2010). To determine more precisely which components of the radar system are responsible for any system biases, the latter two techniques can be combined, as demonstrated in Figueras i Ventura et al. (2012). In particular, the difference between the ZDR derived from solar signals and that obtained from birdbath scans can be used to identify transmitter biases.“...

We have also included your suggestions for the following publications in the introduction:

- Joshil and Chandrasekar (2022; DOI: 10.3390/rs14153534) with respect to sphere calibration,
- Wang et al. (2025; DOI: 10.1109/TGRS.2025.3603593) and also ,
- Schneebeli et al. (2025; DOI:10.5194/amt-18-5157-2025) concerning virtually generated radar targets, and
- Gorgucci et al. (1999; DOI: 10.1109/36.739161) for the birdbath technique.

In Sec. 3 “Calibration of ZDR and ZH“, we come back again to Figueras i Ventura et al. (2012):

...“This potential elevation dependence could be related either to the mechanical control of elevation angles in the BoXPOL scanning strategy or to issues with the rotary joints between the transmitter/receiver and the antenna (private communication with Martin Lennefer and Kai Mühlbauer; Figueras i Ventura et al., 2012)“.

- line 64: "One major benefit and motivation using the QVP..." -> but this is also true for the birdbath scan

Yes, the birdbath scan reduces statistical uncertainties/noise in the averaging process as well. However, the aim was to introduce here part II of the paper series. We deleted the entire sentence to avoid any confusion and because it is not necessary to provide that information about part II.

- line 70: "the results were not reliable for the whole period..." -> Why?

Several problems were identified when applying the offsets derived from the birdbath scans. E.g., during the 2013 - 2014 period, the corrected ZDR values were far too low directly above the ML (see Fig. 4) and also within the liquid phase. In contrast, in 2018 the corrections resulted in too large ZDR values above the ML. Consequently, we decided to calibrate ZDR based on the 18° elevation scans, which are also used for the extensive climatology presented in part II of this paper series. The two figures below illustrate the resulting differences between calibration based on the birdbath scans and on QVPs.

We included a remark in the revised manuscript: ...“Although the birdbath method is widely used to calibrate ZDR, the results were not reliable throughout the entire climatological period. In particular, the offset values obtained for 2014 appeared unrealistically small, limiting the usefulness of the calibrated ZDR.“...

#### 1.4 Radar data:

- line 103: rho\_hv of 0.7 is terribly low. Why do you use such a low threshold? Rain is usually above 0.995 for well calibrated radars.

This is just a first quality threshold within the processing chain. In ensuing steps, e.g. to calibrate ZDR with the QVP methodology or the birdbath scan, to calibrate ZH using the reverse ZH-ZDR relationship, or to employ the self consistency relations, we apply considerably higher thresholds: E.g. rho\_hv > 0.985 in the QVPs methodology following Sanches and Rico-Ramirez (2021) and filter with rho\_hv > 0.99 in the birdbath scan following Pejic et al. (2022). Nethertheless, we deleted the sentence to avoid any confusion.

- line 105: Phase offset processing is not really necessary for Kdp estimation.

Yes, it is not needed for KDP, but we use Filtering with  $\Phi_{DP} < 30^\circ$  as a precautionary measure designed to effectively rule out highly unlikely brief sequences of heavy rain or hail should other thresholds fail. This requires a reliable  $\Phi_{DP}$  offset.

Table 1:

- Radar description: a 0.2us transmit pulse leads to a range resolution of 30 m. So the range resolution you are indicating are averages? Or you are sampling at at 25m resolution?

Indeed, 0.2 microsecond pulse corresponds to 30 m true/intrinsic radial resolution, but signal processing may produce more finely sampled range bins.

- STAR is not really a transmit mode

Agreed, we distinguish now between “Transmit type → Random-phase magnetron using Simultaneous Dual Polarization (SIDpol)“, and “Mode → STAR or SHV“ in Table 1.

- Staggering mode is a transmit mode from my point of view

Table 1 includes now another row with “Dual PRF Unfolding ->Staggered PRF mode 3 (four times unfolding, 4/5 staggering)“.

- What kind of transmitter (Magnetron I guess, but what's the power)?

Information about the magnetron is now included in the Table (see question above) and the magnetron (transmit) peak power is 200 kW (100 kW for the horizontal and vertical channel, respectively).

- Antenna gain = ?

The information about the antenna gain (44.2 dB for both channels) is also added to Table 1 of the revised manuscript.

- What do you mean with high PRF? What's the low PRF then?

BoXPOL operated in dual pulse repetition frequency (PRF) mode 3 to increase the mean velocity dynamic range. Mode 3 uses dual-PRF staggering with a 4/5 PRF ratio and applies four-times unfolding (as mentioned above), thereby increasing the velocity dynamic range by a factor of four. This means that the low PRF is 4/5 of the high PRF.

All information is included in Table 1.

## 1.5 Calibration of Zdr and Zh

~~~~~  

### 1.5.1 Zdr calibration

-----

- line 118: You are using the Probert-Jones Gaussian approximation for the antenna pattern, which can introduce errors of up to 1 dB compared to the usage of the full antenna pattern. Can this be justified?

Yes, the Enigma software operated with BoXPOL employs the Probert-Jones Gaussian approximation in the radar equation. Deviations of the real antenna pattern from the Gaussian approximation may introduce uncertainties in the radar constant. It's not possible to retrieve the actual real error we had for BoXPOL, but +0.5 dB is used for the CSU-CHILL radar to correct the radar constant (Knorr, 2007) and Schneebeli et al. (2025) confirmed the Probert-Jones approximation may lead to errors as high as 0.5 dB. Thus, errors may reach up to 1 dB for BoXPOL. The potential impact on ZH due to the uncertainty in the radar constant caused by the Probert-Jones-Gauss approximation is therefore likely to be less than 1 dBZ and is consequently negligible.

- line 120: You are using  $\theta_h^H$  and  $\theta_v^H$  but only  $G^H$  (similar for both directions). Why?

We initially added two beamwidths,  $\theta_h^H$  and  $\theta_v^H$ , as shown in the Enigma 3 manual, because the Enigma software is also applicable for different radar antenna forms. For BoXPOL,  $\theta_h^H$  and  $\theta_v^H$  are equal (both =  $1.07^\circ$ ) due to the parabolic antenna (this information is also added to Table 1 in the revised manuscript).

We changed that in Sec. 3 "Calibration of ZDR and ZH" accordingly: ..." $K_w$  is the dielectric factor of water,  $\theta^H$  is the half power antenna beam width of the horizontal polarization channel in rad,  $c$  is the speed of light in  $\text{ms}^{-1}$ ,"...

We further deleted  $\theta_h^H$  and  $\theta_v^H$  in Eq. 1 and changed it as follows:

$$Z_H = -10 \log_{10} \left( \underbrace{\frac{\pi^3 |K_w|^2}{\lambda^2 \cdot 1024 \cdot \ln 2 \cdot 10^{18}} P_t^H (G^H \theta^H)^2 c \tau A_t^H A_r^H}_{C_r^H} \right) + 20 \log_{10} r + 10 \log_{10} P_r^H$$

- line 123: If your reference plane is directly behind the antenna, why do you introduce  $A_t$  and  $A_r$ ?

Thanks, you are right. We deleted the sentence accordingly.

- line 136: I don't think that Zdr needs to be calibrated to 0.2 dB for QPE applications.

This statement is supported by e.g., Frech and Hubbert (2020) as well as Ryzhkov and Zrnica (2019). To keep QPE biases within approximately 15%- 20%, a ZDR accuracy of 0.2 dB is required.

- line 141: If you look from below, raindrops appear spherical for Zh and Zv not only in light rain

Correct, we deleted the word “small“ in this sentence.

- line 150 onwards: I don't understand why the birdbath scan should be influenced by the radar hardware, since it is supposed to out-calibrate such effects.

Thanks for this valuable question. The birdbath scan itself is not problematic; however, ZDR offsets derived from birdbath scans are not necessarily applicable to PPIs measured at other elevation angles (e.g. 18°, as used in this study). This is because the radar constants ( $C_r$ ) of the two polarisation channels (H/V) appear to vary with antenna elevation angle. Figure 4 compares ZDR offsets derived from birdbath scans with those obtained using the QVP methodology in light rain at an elevation angle of 18°.

- Also: Consists your hardware of rotary joints or similar equipment or is your transmitter / receiver attached to the antenna directly?

Our hardware consists of rotary joints, so the transmitter/receiver is not directly attached to the antenna.

- Could rotary joints be a source of elevation dependence?

Thank you very much for pointing to this error source.

After discussing with our radar engineer Kai Mühlbauer and our technician Martin Lennefer, rotary joints may indeed cause the elevation dependence. The suggested paper by Figueras i Ventura et al. (2012) is included as additional reference.

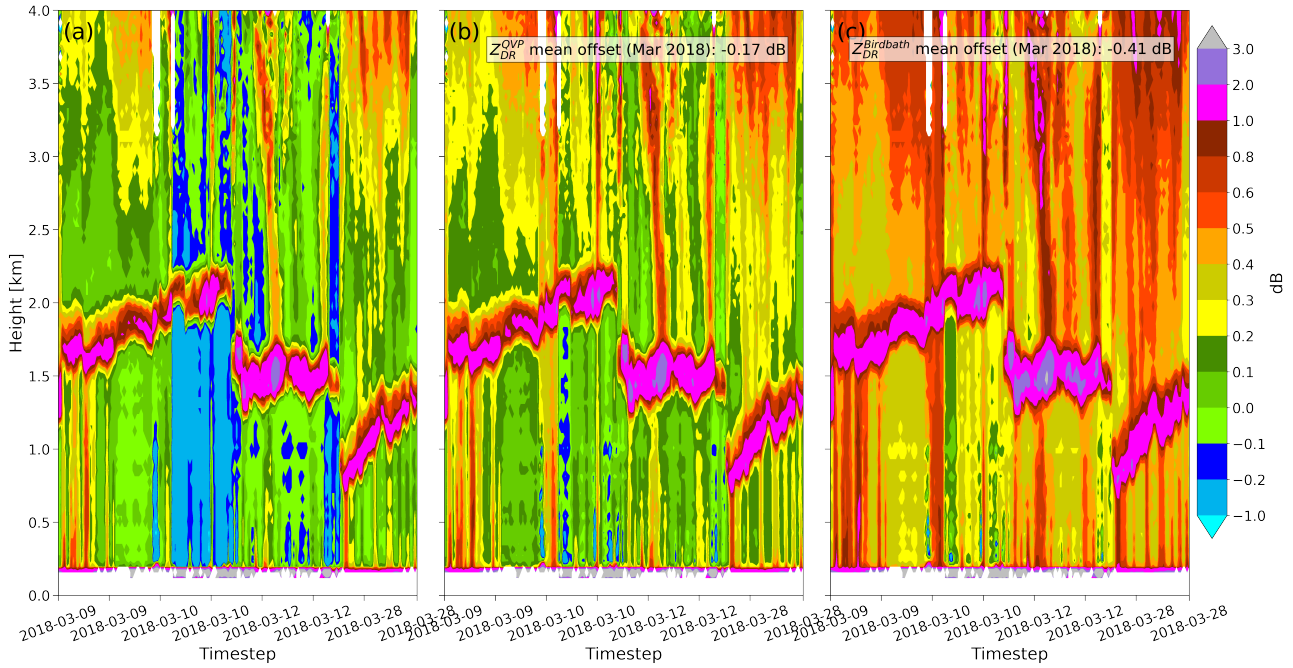
As already mentioned above, we also included in Sec. 3: “This potential elevation dependence could be related either to the mechanical control of elevation angles in the BoXPol scanning strategy, or to issues with the rotary joints between the transmitter/receiver and the antenna (private communication with Martin Lennefer and Kai Mühlbauer; Figueras i Ventura et al., 2012)“...

- In general: I don't fully understand the reasoning here

BoXPol is not operating anymore and it is therefore not possible to modify various settings for comparison and validation purposes. However, our analysis clearly indicates that the ZDR offsets derived from birdbath scans are not appropriate and are therefore nearly unusable for certain time

periods and for PPIs at different elevation angles. A comparison between ZDR offsets derived from QVPs in light rain at the specific elevation angle of  $18^\circ$  and those derived from birdbath scans reveals clear discrepancies, particularly during the period from 2013 to 2014 (see Fig. 5). For 2018, we observe larger ZDR offset values from the Birdbath scan compared to those from QVPs at  $18^\circ$  in light rain. Given the results from 2013 to 2014, in which the birdbath-derived ZDR offsets were indisputably too small, we assume that the birdbath offsets in 2018 (and likely also in subsequent periods) are likewise inaccurate. Possible reasons for the discrepancies are discussed in the manuscript, taking also the BoXPOL logbook into account, but can't be verified retrospectively. As a consequence, we decided to only rely on the ZDR offsets from QVPs in light rain. The figure below shows in the first line exemplary for March 2018, most likely too large ZDR values over the melting layer (panel c) compared to the ones calibrated with QVPs based on scans at  $18^\circ$  elevation angle (panel b)). In February 2014 (shown in the second line of the figure), however, the birdbath-derived ZDR offsets are way too small and not reliable (offset corrected ZDR values stay  $< -0.2$  dB for most of the time and height levels).

March 2018



February 2014

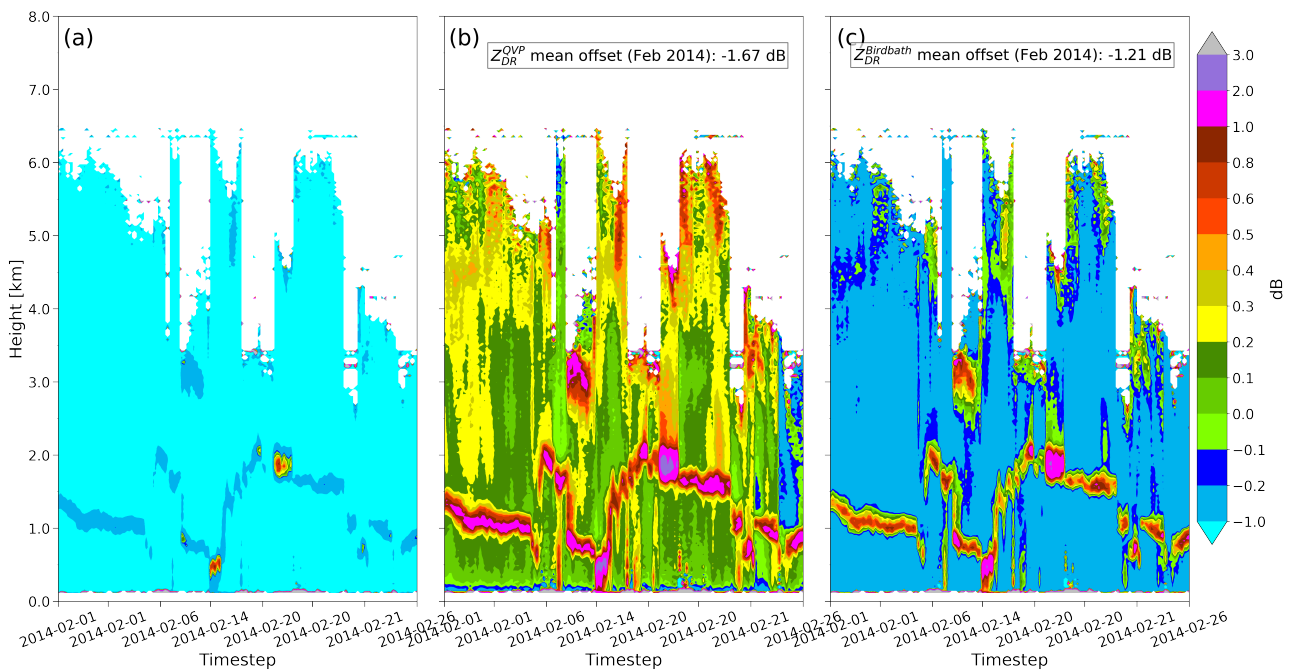


Figure A: QVPs of ZDR not offset corrected (a), offset corrected using QVP method in light rain (b) and birdbath scan method (c) for March 2018 (upper row) and February 2014 (lower row). The mean ZDR offset values for these months of the respective method are given as well. A reliable melting layer is present in all sequences.

- line 166: 10 valid values in the height dimension depends on how you interpolate your range data to a vertical grid

We used `wrl.georef.georeference_dataset`, which applies the function `spherical_to_xyz` to transform the spherical coordinates of the radar to a cartesian grid, as part of the python module `wradlib` (Heisterman et al., 2013). The z coordinate/height information, is calculated following Doviak et al. (1993). No interpolation is applied and each range bin equals one height bin. I.e., 10 valid values in the height dimension equals 10 valid values in the range dimension.

We clarified this in Sec. 2 “Radar data“ of the revised manuscript: ...“The height of the radar beam is calculated assuming 4/3 effective earth radius (e.g., Doviak and Zrnica, 1993). No interpolation is applied, i.e. each range bin transforms into one height bin.“ ...

- line 175: What is the standard deviation of the canting angle? 8 deg as stated in line 177?

Yes, that is correct. We included more precise information about the T-matrix calculations in the revised manuscript: ...“We set the mean canting angle to 0°, with various values for either the temperature (5 °C, 10 °C, 15 °C, 20 °C and 30 °C, respectively) and the width of the canting angle distribution (std(C) with 5°, 8°, 10° and 12°, respectively), applying the raindrop shape model following Brandes et al. (2002).“ ...

- Not sure if sufficient information is provided on how you performed the T-matrix calculations.

T-matrix calculations are performed following Mishchenko et al. (1996) and Mishchenko (2000). We included the references in the revised manuscript and we also point to the python module pytmatrix by Leinonen (2013) in the data and code availability section. “To determine the expected ZDR value, T-matrix simulations (Waterman, 1971; Mishchenko et al., 1996) are performed“ ...

- Are you using the code of Mishchenko?

Yes, we do, see the answer above.

- Can more information on the processing be found in Chen et al. (2021)?

Yes, we refer to Chen et al. (2021) for more information.

- What model of the dielectric constant of water are you using?

To calculate the dielectric factor

$$K_w = \frac{\epsilon_w - 1}{\epsilon_w + 2},$$

where  $\epsilon_w$  denotes the dielectric constant of water.

In the T-matrix simulation (shown in Fig. 2), we follow Ray (1972) to calculate  $\epsilon_w$  for various temperatures between 5 °C and 30 °C.

We added a sentence: ...“The dielectric constant of water ( $\epsilon_w$ ) is calculated for temperatures between 5°C and 30°C following Ray (1972).“ ...

- Line 181: You should also take into account the findings of Zeyong 2019:

<<https://ieeexplore.ieee.org/document/9025914>>

Thank you for this valuable suggestion. We took information from this study into account and refined Sec. 3.1 “ZDR calibration“ as follows: ...“The results are in agreement with those of Sanchez-Rivas and Rico-Ramirez (2022) (with an intrinsic ZDR of 0.18 dB) and Zeyong et al. (2019) (with an intrinsic ZDR in the range from 0.25 to 0.35 dB), despite slightly smaller values in comparison (most likely due to different radar configurations and varying climatic conditions).“ ...

- I also recall that Figueras y Ventura made experiments with Zdr calibration in light rain, but I'm not sure if this is published somewhere.

We were not able to find any published study from Figueras y Ventura about calibration in light rain.

- Line 194: I'm not sure if this argumentation is valid, since (as mentioned) the birdbath scan is supposed to calibrate such hardware changes.

We assumed that the change of the magnetron could have had an influence.

As mentioned above, not the birdbath scan itself is problematic. Instead most likely changes in the H/V channels of the 18° elevation scan influence the radar constants of the two channels ( $C^H$  and  $C^V$ ). The ratio of the radar constant of the 18° elevation scan seems to differ from the ratio of the birdbath scan.

We added an additional sentence plus an equation: ...“The ratios of the radar constants for the birdbath (BB) scan ( $C_{r, BB}$ ) and the 18° elevation scan ( $C_{r, 18}$ ) of the horizontal (H) and vertical (V) polarization channels appear to deviate from each other:

$$\frac{C_{r, BB}^V}{C_{r, BB}^H} \neq \frac{C_{r, 18}^V}{C_{r, 18}^H} .” ...$$

- Figure 4: This figure is using a misleading color scale, since negative values range in an interval between [-0.2 and -1]

This colour scale is intentional because frequently occurring negative ZDR values, especially those smaller than -0.2, are indicating erratic offset corrections. The light blue to cyan colours reveal that the applied ZDR offsets are inappropriate and would lead to misleading/wrong results in quantitative applications, like e.g. QPE.

### 1.5.2 Zh calibration

-----

- You ignore the effect of radome attenuation. What is the consequence?

BoXPoI operated without a radome, thus attenuation effects caused by a wet radome can be ignored. We added this information in Sec. 2 “Radar data“: ...“The hardware includes an EEC DWSR-2001-X-SDP weather radar without a radome, operating in the simultaneous transmit and receive of horizontally and vertically polarized electromagnetic (EM)-waves (STAR or SHV) mode using an Enigma signal processor.“. We also included the info “Radome-less EEC DWSR-2001-X-SDP weather radar“ in Table 1.

- From your curve in Figure 3, a Zh value between 34 and 36 corresponds to a Zdr value between 1 and 1.75, which is a huge range for Zdr but a small one for Zh.
- How can you make an accurate calibration from such a curve?

This is a great question.

The reverse ZH-ZDR method is expected to be most effective within the range of approximately 0 dB to around 0.75-1 dB, where most data points are available from the T-matrix simulations (see Figs. 2 and 3). Nevertheless, the full ZDR range from 0 to 2 dB was used for the observations. To restrict the analysis to days exhibiting the expected positive correlation in pure rain and to exclude e.g. size sorting, a Spearman correlation coefficient of  $> 0.4$  between the corrected ZDR and the uncorrected ZH is required. Additionally, only days with a reliable ZDR offset identified under light rain conditions (the QVPs at  $18^\circ$  elevation) are considered for the determination of the ZH offsets, thereby reducing the occurrence of high ZDR values. The resulting daily ZH offsets are subsequently filtered using only data between the 20th and 80th percentiles, and days with a standard deviation  $> 4$  dBZ are excluded. Finally, the median (rather than the mean) is used to further reduce the impact of outliers.

This stringent filtering process is applied as a compromise to take the whole distribution into account while limiting the influence of large ZDR values, which could result in unrealistic ZH offsets. The figure below illustrates, based on the data for 2013, the impact of ZDR thresholding on the resulting ZH offsets. Limiting the data base to  $ZDR < 1$  dB or making use of all data with  $ZDR < 2$  dB does not result in significant differences for the ZH offset (only a mean abs. difference of 0.208 dBZ). Even the largest differences in the ZH offsets remain below 1 dB. Furthermore, more valid days remain for calibration if the 2 dB threshold is applied.

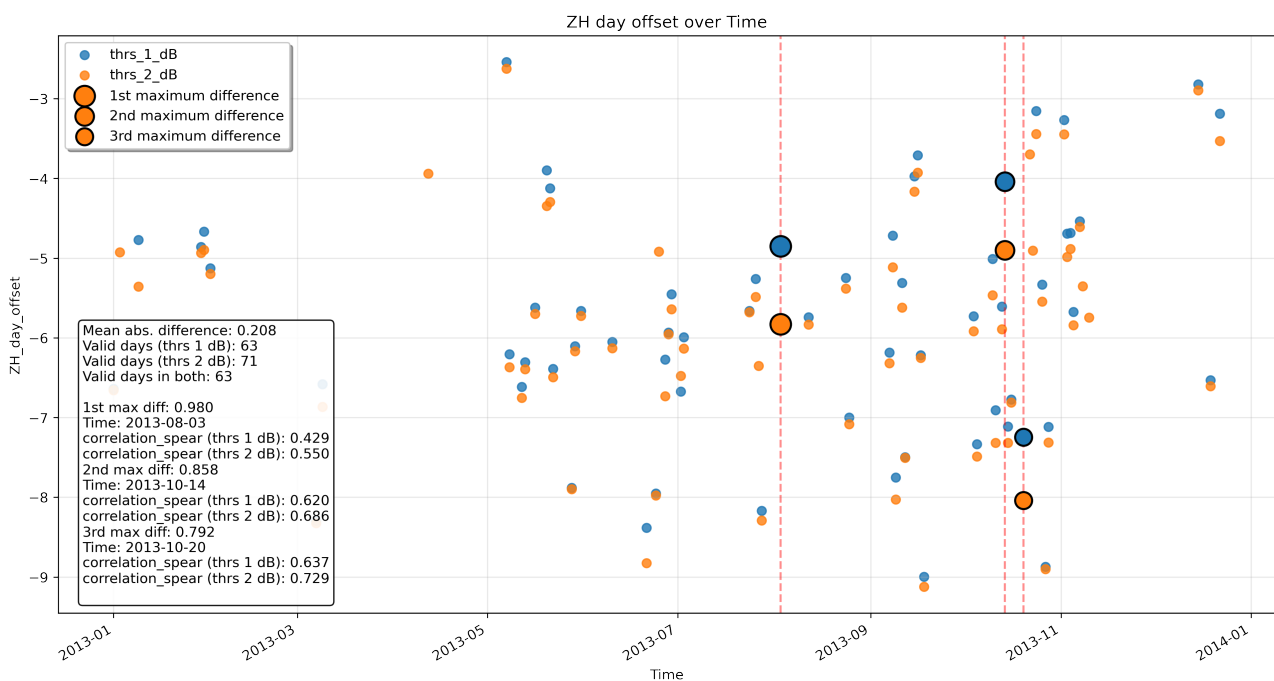


Figure B: Daily ZH offset values for 2013 using the reverse ZH-ZDR method, using a threshold of  $ZDR < 1$  dB and  $ZDR < 2$  dB. The three largest absolute differences are given, as well as the Spearman correlation and the valid days.

- line 224 and Figure 6: This is not really a too convincing fit

As mentioned above, we use now 3 July 2013 as an example instead of 1 January 2013 to enable a better demonstration of the method. Please see the figure below:

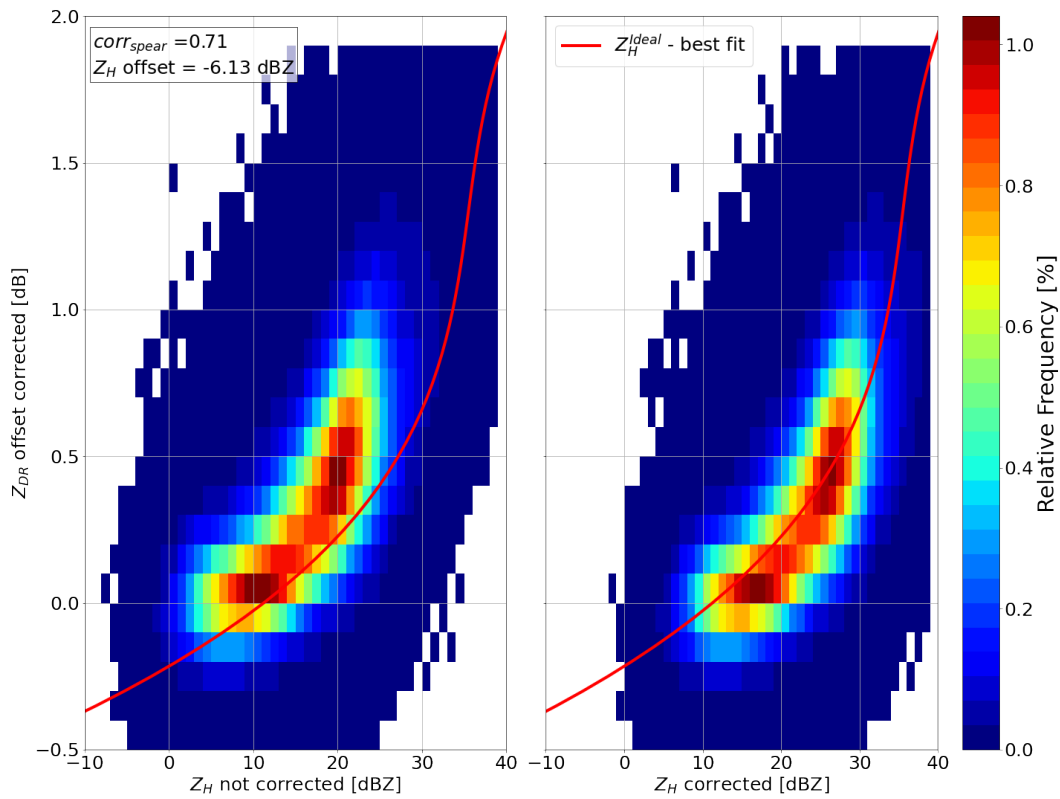


Figure C: Two-dimensional histograms of offset-corrected ZDR versus ZH for 3 July 2013: (a) using uncorrected ZH and (b) using offset-corrected ZH, based on the reverse ZH –ZDR method. The thick red line represents the calculated ideal reflectivity, ZH (Z<sub>ideal</sub>H), corresponding to the best fit.

- line 241: For a comparison

Corrected.

- line 276: 0.25 -0.5 dBZ means 0.25 to 0.5 dBZ?

Thanks, we changed the sentence accordingly.

- Table 3: gap-filled means that the reverse Zdr-Zh algorithm has been applied?  
- I.e., upper row is reverse Zdr-Zh, lower row Kdp-Zh self consistency

Exactly, gap-filled means that the reverse ZH-ZDR method has been applied. Since this might be a bit confusing, we inserted on the left side of Table 3 additional information about the technique used:

| Reverse $Z_H - Z_{DR}$ method: | $Z_H$ offsets (gap filled) | $Z_H$ offsets (gap filled) in RCA stable time periods |
|--------------------------------|----------------------------|-------------------------------------------------------|
| RMSE [dBZ]                     | 1.88                       | 0.70                                                  |
| MAE [dBZ]                      | 1.51                       | 0.60                                                  |
| MB [dBZ]                       | -0.36                      | -0.50                                                 |
| Self-consistency relations:    | $Z_H$ offsets (gap filled) | $Z_H$ offsets (gap filled) in RCA stable time periods |
| RMSE [dBZ]                     | 2.28                       | 1.62                                                  |
| MAE [dBZ]                      | 1.91                       | 1.37                                                  |
| MB [dBZ]                       | 1.14                       | 1.37                                                  |

- line 295: I'm not convinced that the reverse Zdr-Zh algorithm outperforms the Kdp self consistency.

Based on the error metrics, especially the root mean square error (RMSE) and mean absolute error (MAE), the proposed reverse ZH-ZDR method outperforms the self-consistency method. The results are based on the 5.5 years of BoXPOL data for which the satellite-based calibration offsets are available. However, different results may occur for other radars or different circumstances. The reverse ZH-ZDR method should be tested and validated in different climate regions and for various radars (also operating with other wavelengths) in the future.

We added the following paragraph in Sec. 4 “Summary, discussion and outlook“:

...“We do not intend to suggest that the self-consistency method is generally inferior. Rather, we wish to emphasize that BoXPOL’s ZH was calibrated with the method introduced with sufficient accuracy and, compared with an already established method, with even greater precision.“...

- Kdp is independent of radome attenuation, which is not true for Zdr.

BoXPOL did not operate with a radome, thus wet radome attenuation (or any other potential influences of a radome) can be ignored.

- In addition the Zdr - Zh relation is ambiguous (as mentioned before)

Problematic days are limited by the threshold applied (daily standard deviation of ZH < 4 dBZ) and prior filtering to restrict to data between the 20th and 80th percentile. Furthermore, only days for which precise ZDR offset values have been determined using QVPs in light rain are considered (daily standard deviation of ZDR < 0.2 dB).

- Just because it fits better to the satellite is not a strong argument

Spaceborne radar observations (particularly those from the GPM DPR) have become a widely accepted reference for calibrating ground-radar ZH. Several studies have used volume-matched GPM or TRMM based ZH for ground-based ZH calibration, to improve radar network consistency and/or to validate operational calibration procedures (see e.g. Warren et al., 2018; Crisologo et al.,

2018; Louf et al., 2019; Loulli et al., 2025; Protat et al., 2022; Pejcic et al., 2022; Anagnostou et al., 2001).

In the revised manuscript, we included more references in Sec. 3.2.2 “Validation of ZH-calibration using satellite information“ to further emphasize the widespread and accepted use of spaceborne measurements for calibration: ...“Satellite measurements of the Dual-frequency Precipitation Radar (DPR) operating on the Global Precipitation Mission (GPM; e.g. Hou et al., 2014; Pejcic et al., 2020) core satellite, as well as its predecessor the Tropical Rainfall Measurement Mission (TRMM; see e.g. Kozu et al., 2001; Joss et al., 2006), have been demonstrated to be a valuable data source for the calibration of ground based ZH radar measurements (e.g., Pejcic et al., 2022; Louf and Protat, 2023; Louf et al., 2019, Warren et al., 2018; Loulli et al., 2025; or Anagnostou et al., 2001.)“ ...

Furthermore, we updated the last section with the following: ...“Further validation of the reverse ZH-ZDR method in different climate regimes, at different radar wavelengths, and with an increased number of GPM overflights, should be carried out in the future.“ ...

- If you compare to the satellite anyway, why not taking the offsets obtained from satellite comparisons directly?

Trömel et al. (2023) published a 5.5-year subset that used ZH offsets based on satellite data published by Pejcic et al. (2022).

In this two-part paper series, we extended their climatology to 10 years and aimed to utilise a calibration method that permits a finer time resolution. However, satellite calibration is dependent upon overflights, and the sample size for the 5.5-year period is only 92. The self-consistency method, e.g., yielded 148 valid days for ZH offset calibration in the full ten-year period presented in our study, whereas the reverse ZH-ZDR method provided 544 valid days.

The larger sample size suggests broader applicability, which could also have a positive impact on gap-filling methods.

Comparing the satellite-derived ZH offsets point-to-point with those from the self-consistency method and the reverse ZH-ZDR method for the same valid days for all three methods (giving a sample size of 20 days), we observe that the error metrics (RMSE and MAE) are still lower for the latter than the former, further increasing confidence in the proposed reverse ZH-ZDR methodology. Another important point is the possibility of phase processing-related issues affecting the reliability of KDP for successful application of the self-consistency methodology.

Further informations are implemented in Sec. 3.2.2 “Validation of ZH-calibration using satellite information“ as follows:

...“Daily average ZH offsets based on the differences between measurements of BoXPOL and the satellite-based Ku-band radar (part of DPR, explained in more detail in Pejcic et al., 2022) are compared with daily offsets obtained using the reverse ZH-ZDR method and the self consistency relations (see Fig. 10). The reverse ZH-ZDR method provides 544 daily ZH offsets, whereas the self-consistency method only provides 148 days.“ ...

...“In summary, since the self-consistency method bears several uncertainties, as well as a smaller sample size compared to the reverse ZH-ZDR method (148 versus 544 valid days) and more confidence can be assigned to the comparison with satellite overflights, we conclude on the overall reliability of the reverse ZH-ZDR method for ZH calibration.“ ...

## References:

- Anagnostou, E. N., Morales, C. A., and Dinku, T.: The use of TRMM precipitation radar observations in determining ground radar calibration biases, *Journal of Atmospheric and Oceanic Technology*, 18, 616–628, [https://doi.org/10.1175/1520-0426\(2001\)018<0616:TUOTPR>2.0.CO;2](https://doi.org/10.1175/1520-0426(2001)018<0616:TUOTPR>2.0.CO;2), 2001.
- Brandes, E. A., Zhang, G., and Vivekanandan, J.: Experiments in rainfall estimation with a polarimetric radar in a subtropical environment, *Journal of Applied Meteorology and Climatology*, 41, 674–685, [https://doi.org/10.1175/1520-0450\(2002\)041<0674:EIREWA>2.0.CO;2](https://doi.org/10.1175/1520-0450(2002)041<0674:EIREWA>2.0.CO;2), 2002.
- Chen, J.-Y., Trömel, S., Ryzhkov, A., and Simmer, C.: Assessing the benefits of specific attenuation for quantitative precipitation estimation with a C-band radar network, *Journal of Hydrometeorology*, 22, 2617–2631, <https://doi.org/10.1175/JHM-D-20-0299.1>, 2021.
- Crisologo, I., Warren, R. A., Mühlbauer, K., and Heistermann, M.: Enhancing the consistency of spaceborne and ground-based radar comparisons by using beam blockage fraction as a quality filter, *Atmospheric Measurement Techniques*, 11, 5223–5236, <https://doi.org/10.5194/amt-11-5223-2018>, 2018.
- Doviak, R. J. and Zrníc, D. S.: *Doppler Radar and Weather Observations*, Academic Press, San Diego, 2nd edn., <https://doi.org/10.1016/C2009-0-22358-0>, 1993.
- Figueras i Ventura, J., Boumahmoud, A., Fradon, B., Dupuy, P., and Tabary, P.: Long-term monitoring of French polarimetric radar data quality and evaluation of several polarimetric quantitative precipitation estimators in ideal conditions for operational implementation at C-band, *Quarterly Journal of the Royal Meteorological Society*, 138, 2212–2228, <https://doi.org/10.1002/qj.1934>, 2012.
- Frech, M. and Hubbert, J.: Monitoring the differential reflectivity and receiver calibration of the German polarimetric weather radar network, *Atmospheric Measurement Techniques*, 13, 1051–1069, <https://doi.org/10.5194/amt-13-1051-2020>, 2020.
- Heistermann, M., Jacobi, S., and Pfaff, T.: Technical note: An open-source library for processing weather radar data (wradlib), *Hydrology and Earth System Sciences*, 17, 863–871, <https://doi.org/10.5194/hess-17-863-2013>, 2013.
- Holleman, I., Huuskonen, A., Gill, R., and Tabary, P.: Operational monitoring of radar differential reflectivity using the sun, *Journal of Atmospheric and Oceanic Technology*, 27, 881–887, <https://doi.org/10.1175/2010JTECHA1381.1>, 2010.
- Knorr, J. B.: Weather radar equation correction for frequency-agile and phased-array radars, *IEEE Transactions on Aerospace and Electronic Systems*, 43(3), 1220–1227, <https://doi.org/10.1109/TAES.2007.4383614>, 2007.
- Louf, V., Protat, A., Warren, R. A., Collis, S. M., Wolff, D. B., Raunyar, S., Jakob, C., and Petersen, W. A.: An integrated approach to weather radar calibration and monitoring using ground clutter and satellite comparisons, *Journal of Atmospheric and Oceanic Technology*, 36, 17–39, <https://doi.org/10.1175/JTECH-D-18-0007.1>, 2019.

- Loulli, E., Michaelides, S., Bühl, J., Loukas, A., and Hadjimitsis, D.: Calibration of two X-band ground radars against GPM DPR Ku-band, *Remote Sensing*, 17, 1712, <https://doi.org/10.3390/rs17101712>, 2025.
- Mishchenko, M. I.: Calculation of the amplitude matrix for a nonspherical particle in a fixed orientation, *Applied Optics*, 39, 1026–1031, <https://doi.org/10.1364/AO.39.001026>, 2000.
- Mishchenko, M. I., Travis, L. D., and Mackowski, D. W.: T-matrix computations of light scattering by nonspherical particles: A review, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 55, 535–575, [https://doi.org/10.1016/0022-4073\(96\)00002-7](https://doi.org/10.1016/0022-4073(96)00002-7), 1996.
- Pejcic, V., Saavedra Garfias, P., Mühlbauer, K., Trömel, S., and Simmer, C.: Comparison between precipitation estimates of ground-based weather radar composites and GPM's DPR rainfall product over Germany, *Meteorologische Zeitschrift*, <https://doi.org/10.1127/metz/2020/1039>, 2020.
- Pejcic, V., Soderholm, J., Mühlbauer, K., Louf, V., and Trömel, S.: Five years of calibrated observations from the University of Bonn X-band weather radar (BoXPol), *Scientific Data*, 9, 1–9, <https://doi.org/10.1038/s41597-022-01656-0>, 2022.
- Protat, A., Louf, V., Soderholm, J., Brook, J., and Ponsonby, W.: Three-way calibration checks using ground-based, ship-based, and space-borne radars, *Atmospheric Measurement Techniques*, 15, 915–926, <https://doi.org/10.5194/amt-15-915-2022>, 2022.
- Ray, P. S.: Broadband complex refractive indices of ice and water, *Applied Optics*, 11, 1836–1844, <https://doi.org/10.1364/AO.11.001836>, 1972.
- Ryzhkov, A. V. and Zrnić, D. S.: *Radar Polarimetry for Weather Observations*, Springer International Publishing, <https://doi.org/10.1007/978-3-030-05093-1>, 2019.
- Sanchez-Rivas, D. and Rico-Ramirez, M. A.: Calibration of radar differential reflectivity using quasi-vertical profiles, *Atmospheric Measurement Techniques*, 15, 503–520, <https://doi.org/10.5194/amt-15-503-2022>, 2022.
- Schneebeli, M., Leuenberger, A., Frech, M., and Ventura, J.: Weather radar data calibration and monitoring, *Advances in Weather Radar*, 2, 41–97, [https://doi.org/10.1049/SBRA557G\\_ch2](https://doi.org/10.1049/SBRA557G_ch2), 2024.
- Schneebeli, M., Leuenberger, A., Schmid, P. J., Grazioli, J., Corden, H., Berne, A., Kennedy, P., George, J., Junyent, F., and Chandrasekar, V.: Calibration of weather radars with a target simulator, *Atmospheric Measurement Techniques*, 18, 5157–5176, <https://doi.org/10.5194/amt-18-5157-2025>, 2025.
- Trömel, S., Blahak, U., Evaristo, R., Mendrok, J., Neef, L., Pejcic, V., Scharbach, T., Shrestha, P., and Simmer, C.: Fusion of radar polarimetry and atmospheric modeling, in: *Advances in Weather Radar, Volume 2: Precipitation Science, Scattering and Processing Algorithms*, The Institution of Engineering and Technology (IET), [https://doi.org/10.1049/SBRA557G\\_ch7](https://doi.org/10.1049/SBRA557G_ch7), 2023.
- Warren, R. A., Protat, A., Siems, S. T., Ramsay, H. A., Louf, V., Manton, M. J., and Kane, T. A.: Calibrating ground-based radars against TRMM and GPM, *Journal of Atmospheric and Oceanic Technology*, 35, 323–346, <https://doi.org/10.1175/JTECH-D-17-0128.1>, 2018.
- Waterman, P. C.: Symmetry, Unitarity, and Geometry in Electromagnetic Scattering, *Physical Review D*, 3, 825, <https://doi.org/10.1103/PhysRevD.3.825>, 1971.

Zeyong, G., Zhaoping, S., jia, G., Feifei, L., and Zhichao, B.: A Method for Calibrating Zdr by Using Light Rain Echo in Volume Scan Data, in: 2019 International Conference on Meteorology Observations (ICMO), p. 1–3, IEEE, <https://doi.org/10.1109/icmo49322.2019.9025914>, 2019.