Interactive comment on ”Calibration of radar differential reflectivity using quasi-vertical profiles”. Response to Anonymous Referee 1

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We thank the reviewer for the insightful review of the manuscript and for the interesting feedback that surely will improve our work. In the following, we provide our answers (in blue) to the reviewer comments (in black), highlighting the key points of each paragraph (bold black).

General Comments:

This manuscript offers a method for monitoring the ZDR offset of a dual-polarization radar using quasi-vertical profiles (QVP). The method is applied on C-band weather radars in light rain media. The authors suggest accuracy to O[0.1 dB], e.g., potentially in-line with 'bird-bath' calibration (natural media). There are two apparent justifications for this publication: **its improvement compared to previous natural media efforts**, and its QVP application towards these ideas.

1. *We consider that our method targeting **natural media** (i.e., light rain) is applicable when birdbath scans are not available, but **we are not suggesting that our approach is better** or should replace the well-known Z_{DR} calibration method based on 90° VPs. In fact, the performance of our method is relative to the performance of the VP-based Z_{DR} calibration method. The VP-based calibration method should be used where possible, providing that VP scans are available and there is rainfall above the radar. However, if this is not the case, our QVP-based Z_{DR} calibration method is a very good alternative. As with any other method, ours faces advantages and disadvantages as discussed in the following paragraphs.*

The manuscript is not recommended for publication. The study is functional with elements similar to the typical AMT scope, but the reviewer finds **low value in the 'new' concept/application**. The use of intrinsic liquid properties for ZDR monitoring is well known, origins in low angles and selective ZDR averages (i.e., cell peripheries). **This manuscript adds a "QVP"-wrapper aimed now at liquid media, yet lacks the physical underpinning as to why such methods would improve performance over a boilerplate practice to 'average ZDR in light rain'. These "QVP" concepts are evaluated against a modest dataset, but reads to the reviewer as motivated by convenience and applying a poorly-matched "QVP" concept** (hammer looking for a nail?) in a less-behaved condition (light rain) to be 'novel'. Yet, it seems **a straightforward evaluation of an existing snow QVP application (as less original as that seems) may have been far less controversial.** The authors perhaps unintentionally increased their degree of difficulty (at least, to this reviewer), by leaving the reviewer questioning whether simpler, quicker, or (existing dry snow) options for targeted averaging may be equally/more effective.

2. *We consider that **this new application of the QVPs is needed** because several weather radar networks worldwide are leaning towards providing the QVPs as an operational product. We understand that the use of QVPs can be controversial due to the averaging process required for their construction. However, several works (see Allabakash et al. (2019); Griffin et al. (2018); Lukach et al. (2021); Ryzhkov et al. (2016); Trömel et al. (2019) for example) have demonstrated the ability of QVPs to detect the melting layer (ML), correct the vertical*

profile of reflectivity (VPR) variation, classify hydrometeors or monitor the Z_{DR} calibration. Hence, we felt there was a research gap related to the use of QVPs to detect the offset in Z_{DR} worth to be explored.

3. *We set* ***"Can the QVPs capture the Z_{DR} offset if constrained to heights/ranges close to the radar and making sure the profiles depict light rain and stratiform events?"*** *as the main research question of the present study, and we believe that we demonstrated that the Z_{DR} offset can be accurately detected if some constraints are applied to classify the QVPs. We consider that we provided a solid foundation of our method in Section 3, but we are aware some ideas were not thoroughly described. We will amend this issue in a revised version of the manuscript taking into account the reviewer's suggestions.*

4. *As mentioned above,* ***we do not consider that our method outperforms the boilerplate practice*** *of detecting the Z_{DR} offset using VPs in light rain. Instead, we reckon we provided an operational "QVP"-wrapper for radars not capable of pointing the antenna at high elevation angles ($> 10°$). Additionally, we evaluated the proposed QVP-method against VPs built from two radar sites throughout one year of data and an extensive set of disdrometer data located near the radar sites. Although we presented only one case study in the manuscript (Section 4.2.1) for practicality's sake, we did not hand-picked events convenient to our research. Instead, we present a long-term evaluation of our method (as shown in Figures 8-10 in the manuscript) that includes different types of rain events, ranging from light to heavy rain. We consider this evaluation process demonstrates the efficacy of the proposed constraints to filter unsuitable QVPs.*

5. *We want to clarify that* ***we performed a straightforward evaluation of the dry-snow approach*** *to calibrate Z_{DR} using QVPs. However, several aspects hampered its application on our datasets. First, the dry-snow based method would require a previous hydrometeor classification to detect such types of targets. From our point of view, it is not possible to implement an accurate hydrometeor classifier without having an offset-corrected version of Z_{DR}. However, we are aware that dry aggregated snow is universally present above the melting layer in stratiform clouds (Ryzhkov et al., 2005). Thus, we analysed hundreds of polarimetric profiles (both VPs and QVPs datasets described in the manuscript) and found that distinctive signatures of dry snow are only clearly visible on the VPs. This agrees with the findings of Ryzhkov et al. (2005) in which signatures of dry snow are clearly visible in QVPs built from higher elevation angles ($\sim 40° - 60°$). Unfortunately, it is not possible to generate QVPs at such elevation angles using data from the UK Met Office radar network, as the higher tilt for QPE applications is $9°$. Conversely, in the QVP data set, we observed values of Z_{DR} in the rain medium (i.e., below the melting layer (ML) bottom) that contrasted to those observed aloft. Figure 6 of the manuscript exemplify this issue, in which values close to the melting level are different from those observed in liquid media. This is probably due to the beam broadening and non-uniform beam filling (NUBF) effects, expected when the QVPs intercept the ML and regions above at $9°$ elevations. This is the reason why we cannot use QVPs from these relatively low elevation scans and set dry-snow as the target to derive the Z_{DR} offset.*

Moreover, a central claim for this effort seems to follow its **'relative' calibration performance (oversold), esp. for "light rain".** It is unlikely any 'natural' method can genuinely guarantee accuracy better than 0.2-0.3 dB – this has been well-argued by previous authors, including several cited; Prior efforts were rightfully cautious in their claims. Yes, some allowance can also be extended to older studies that are occasionally captives to their moment (i.e., radar technology improves with time $\rightarrow$ better ability to target lighter rain, etc.). Nevertheless, the intrinsic "light rain" variability is significant and comes in many forms (not limited to):

- Capabilities to provide 'ground truth' (e.g., disdrometers as a poor light rain reference);
- What gets defined as 'light rain' (regional / physical process variability),

- How one identifies these regions with existing radar (Z calibration, etc.), and Location, radar sensitivity/quality, other vertical profile factors (e.g., evaporation, sorting, process) that undermine accuracy claims when averaging over regions.

6. *We agree with the reviewer on the point that we perform a relative evaluation to the VPs method. Furthermore, the stated accuracy of our method across the manuscript is relative to the VPs and this shall be clearly indicated in the revised version of the manuscript. However, we consider that the long-term comparison between the proposed method and the well-known VP-based Z_{DR} calibration method confirms the validity of our method, as shown in manuscript Figures 7-9. Moreover, we do not only used VPs to assess the performance of our method, but we also validated our results with disdrometer data. We observed good agreement between our results and the disdrometer data, considering the well-known discrepancy when comparing radar data to a fixed point location, as shown in Figures 10-11.*

7. *We agree that the concept of light rain can vary upon several factors, like radar calibration and its geographical conditions. However, we consider that the proposed range (0-20 dBZ) is not that far to what Bechini et al. (2002); Fabry (2015); Yang et al. (2019), amongst others define as light rain (5-35 dBZ), considering that the QVPs represent an average of the PPI scan. Finally, it is worth noting the UK Met Office continuously monitors the quality of the radar reflectivity (Harrison et al., 2012, 2017), hence we consider that this does not add uncertainty into our analysis.*

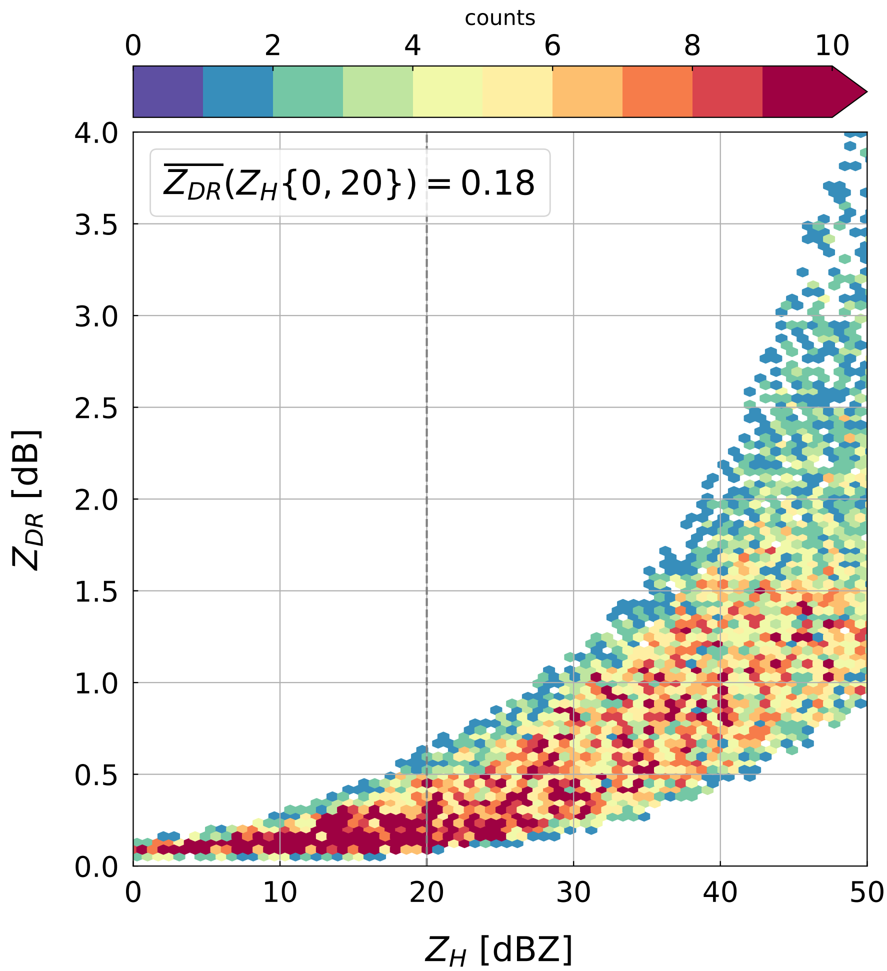
For this reviewer,the authors have not demonstrated they built a better mousetrap. The reviewer understands there is an inevitable overconfidence (aka, marketing) in most manuscripts. However, “relative”, not absolute calibration concepts are typically quite conservative, and it should be obvious that selective performance may be better under ideal conditions. The authors’ disdrometer image (Figure 5) alludes to some inherent variability in (surface, ‘instantaneous’) **ZDR properties in “light rain” (aka, dynamic range of intrinsic ZDR > 0.6 dB)**. These depictions are consistent with discussions by Bechini et al., Ryzhkov et al., for what those authors expect from “light rain”, or why “light rain” (generic) is less suitable than “dry snow” (see also, specific comment). Select locations (UK) experience different bulk microphysical expectations (e.g., propensity for widespread rainfall, stratocumulus), thus **performances may reflect strong local process / natural advantages (e.g., contrast with “light rain” at the peripheries of thunderstorms)**.

8. *We agree that there is an inherent variability of Z_{DR} in light rain. As stated in point 5, we cannot use natural targets with no Z_{DR} variability like dry snow (inherent value close to 0 dB), hence we proposed light rain as target but with thresholds ($(0 < Z_H < 20)$ that minimise this variability. This range is a compromise to avoid having significant variations on Z_{DR} but still keeping enough QPVs into the analysis that enable a reliable detection of the Z_{DR} offset.*

9. *We agree with the reviewer that our disdrometer data may reflect UK local processes. To address this issue, we simulated a wide range of DSDs using the range of parameters described in Bringi and Chandrasekar (2001) expected in real storm events:*

$$10^3 \leq N_w \leq 10^5 \ [mm^{-1} m^{-3}]$$
$$0.5 \leq D_0 \leq 2.5 \ [mm]$$
$$-1 \leq \mu \leq 5$$
$$R \leq 300 \ [mm\ h^{-1}]$$

We randomly generated 10,000 sets of DSD parameters (Nw, D_0 and μ) uniform-distributed within the ranges defined above. Equation 3 from the paper was used to simulate the DSDs, which were used as input to a T-matrix scattering model to compute Z_H and Z_{DR}. The scattering simulations were performed using the same assumptions as described in the *manuscript: (i) the raindrop shape model from Thurai et al. (2007) (their Eq. 2 for $D > 1.5$ mm, their Eq. 3 for $0.7 <= D <= 1.5$ mm, spherical raindrops otherwise); (ii) no canting angle distribution; (iii) maximum diameter for the integration fixed to $3D_0$; (iv) temperature of $10°$ C, radar wavelength of 5.3 cm and elevation angle of $0°$. The results are shown in Figure 1, which depicts the theoretical variation of Z_{DR} versus Z_H. We computed the Zdr bias in light rain and this gives a value of $\overline{Z_{DR}} = 0.18dB$ for $Z_H < 20$ dBZ, which is consistent with the result obtained using measured DSDs.*



Revision Figure 1: $Z_H - Z_{DR}$ dependencies using random values of N_w / D_0 / μ

Overall, one takeaway message is that this reviewer does not feel the authors have justified the "QVP" application as a genuine improvement over a generic "average" ZDR monitoring practice, for rain, snow or otherwise. Rather, **the reviewer claim may be that "QVPs" in light rain are arguably far worse**, given this form of averaging enables mixtures of less suitable profile properties that produce apparently viable "light rain" profiles. Why use a "QVP" process at all? Fundamentally, this is a reduction of information; Many previous studies speak to physical 'profile' issues convolved with "QVPs" and similar averaging, with even the QVP originators shifting to "CVPs" or other targeted averages – For example, ZDR should naturally evolve below the melting layer in response to processes such as sorting, evaporation, break-up, and/or other regime-averaging nuances (within event, or tropical vs midlatitude differences). This all points to why previous studies may have remained cautious in their claims on relative 'light rain' use and uncertainty, but also where QVP-ideas are suboptimal (esp. in rain, below cloud, etc.). The reviewer is questioning the need in using a QVP in these contexts if the QVP cannot be justified as out-performing any number of simpler, targeted ZDR averages of 'light rain' (if one is already thresholding regions loosely on Z, RHV regardless, you've already opened that echo classification bag once one introduced decision-tree thresholding for 'drizzle', etc).

10. *We agree that the inherent averaging process in the QVP construction may wash out some key microphysical processes within the precipitation events. However, Ryzhkov et al. (2016) demonstrated the usability of QPVs in radar meteorology, in particular, to monitor the calibration of Z_{DR}. Moreover, we consider that the averaging process to build the QVPs and the proposed constraints to filter profiles not related to light rain is particularly effective in this situation. We proposed several restrictions to identify suitable QVPs that capture the Z_{DR} offset. For instance, our method requires a proper detection of the ML within the QVPs to ensure that the computation of the Z_{DR} offset is reliable. Allabakash et al. (2019); Griffin et al. (2020); Lukach et al. (2021); Sanchez-Rivas and Rico-Ramirez (2021) demonstrated that heights of the ML top and bottom can be accurately estimated using QVPs. We consider that QVPs without ML signatures are filtered by this requirement, thus reducing the uncertainty of using QVPs of polarimetric variables.*

Specific Comment:

Why do the authors use "light rain" for the "QVP"? Many efforts point to why they avoid light rain (see, Ryzhkov et al, discussions). Unfortunately, **the reviewer might have been more amenable to an AMT manuscript that was simply a long-term validation for an existing 'dry snow' QVP concept.** That is because most "QVP" concepts and ZDR calibration at higher tilts focus on the properties of lower density, dry aggregate snow as a claimed better-case media. They often note that the spatiotemporal averaging/variability is still a concern, but perhaps less **in-cloud and widespread stratiform selective events**. Overall, those rationale (e.g., Ryzhkov et al. and subsequent) reflect a somewhat different take on the role of higher tilts and the expected ranges for ZDR media at higher tilts. The current authors use expressions such as:

> "The intrinsic value of Z_{DR} for angles below 90° and collected in light rain is different from zero. Also, it is elevation-dependent, as demonstrated by Bringi and Chandrasekar (2001) and formulated by Ryzhkov et al. (2005) as:"
>
> $$Z_{dr}(\theta) \approx \frac{Z_{dr}(0)}{\left[Z_{dr}^{1/2}(0)\sin^2\theta + \cos^2\theta\right]^2} \tag{8}$$

11. *As stated in point 5, we did carry out a long-term validation of the existing 'dry snow' not only on QVPs but also on VPs. We observed that dry snow is an excellent alternative to calibrate Z_{DR} using scans taken at vertical incidence, as demonstrated by Ferrone and Berne (2021) or really high elevation angle scans (40°–60°), as shown by Ryzhkov et al. (2005). However, this is not the case for QVPs built from 9° tilts in which targeting the dry snow above the ML exacerbate the NUBF issue; as the range increases, there is a bigger chance of the beam intercepting mixed-phase hydrometeors. This is why we explored the use of light rain in QVPs. We wanted to provide an operational alternative to radars with similar configurations that cannot collect high elevation scans nor birdbath scans.*

The reason **Ryzhkov et al. give for higher tilts and dry snow** is seemingly opposite to the current authors' logic – Ryzhkov argues **dry snow has lower natural ZDR variability**, and when these media are viewed from higher tilts (e.g., the eventual multiplier on ZDR in equation (9) would be closer to 0 instead of 1), the dynamic range of potential ZDR variability is low. When the underlying media experiences a wider range of variability, aka, light rain ranges from 0.1 dB to 0.6+ dB at typical trusted Z ranges, etc., this implies added uncertainty for any 'average' reference frame. These issues are at their most problematic at grazing angles, and possibly not preferable at lower altitudes (given evaporation, other profile physical processing that evolves ZDR below cloud). Thus, it is not immediately preferable (for their concepts) to have:

$$Z_{dr}(\theta = 10°) \approx 0.968 Z_{dr}(\theta = 0°)\,[dB] \tag{9}$$

e.g., a high coefficient close to 1 is 'bad' for "light rain" in these contexts, b/c the intrinsic ZDR for $Z \sim$ 15-20 dBz remains in those ranges from 0.1 to 0.6 dBz (aka, author Figure 5); This drives the potential uncertainty against the 'reference' ZDR, and one may be correcting by > 0.3 dB quite often (perhaps this was worse in Oklahoma, where lower, unregulated use of Z caries a wider range of ZDR). High tilt intrinsic property sampling (if available, aka, 'birdbath' at its limit) acts to limit that range of possible ZDR → better chance to accurately pinpoint ZDR. Thus, the authors' statement,

> "Hence, ZDR radar measurements collected at elevation angles below 10° are similar to those collected at lower elevation angles and so they do not add additional uncertainty to the offset correction method."

... feels opposite this 'dry snow' rationale. This seems to be a question of whether the authors genuinely believe they can target low-ish variability ZDR 'drizzle' better than low-variability dry snow? This may be regional to the UK, e.g., stratocumulus w/drizzle, but may not seem as reasonable if painted with a US NEXRAD radar lens, as a separate example.

12. *We agree that methods based on vertical measurements (Gorgucci et al., 1999) or really high tilts (Ryzhkov et al., 2005) are excellent options if such scans are available and we consider that must be used when possible. However, we want to provide an alternative to radars not capable of performing scans at such elevations.*

13. *We agree on the point that dry snow has lower natural Z_{DR} variability compared to light rain when using high tilts (40°-60°). But this variability increases at lower elevations, and the QVPs are affected by this issue. This is why we restricted the height within the QVPs along with thresholds in ρ_{HV} in an effort to keep the variability at the minimum. Moreover, we agree with the reviewer that our method may be restricted to QVPs depicting weak, stratiform rain. Still, as mentioned in point 10, it is possible to apply several methods to detect the ML boundaries and stratiform rain events. Thus, we consider that if such conditions are met, our approach yields reliable estimations of the Z_{DR} offset. We will discuss this further on the revised version of the manuscript.*

Even with light rain, these issues are likely worse than presented; For example, this effort has not fully discussed that the disdrometer (Parsivels, etc.) references are poor in light rain R ¡ 1-3 mm/hr. It is unlikely most units capture light rain properties perfectly, esp. with assumptions made for disdrometer processing (a different subset of literature on Parsivel, 2DVD and other light rain comparisons). Dry snow media, similarly, has its own issues with identification, wavelength dependency, complications to "QVP" profiles from non-uniform beam-filling (at C-band, there is potentially intrinsic negative ZDR above the ML owing to non-uniform beam filling!). There is not a quick fix, unfortunately.

14. *We performed a new procedure to estimate the Z_{DR} reference value as described in point 9. We consider that this new approach reduces the uncertainty on using a reference value that may reflect local processes, as it was computed using a range of parameters expected in real storm events. Also, note that the validation provided in Figures 9-11 in the manuscript reflects precipitation events collected throughout one year of data. Hence not only light rain events are analysed, but heavy rain events are included as well.*

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