

## Response to Reviewer #1 of egusphere-2026-1453

Dear Reviewer #1,

Thank you very much for taking your time to evaluate our paper. Your comments are greatly helpful to improve the manuscript. We have revised the manuscript based on reviewers' comments as explained below with point-by-point responses to your comments. We believe that the revision appropriately addresses your comments and questions on the original manuscript, and hope that our revised manuscript now deserves to be published in *Atmospheric Measurement Techniques*.

**[RC]: Reviewer's comment**

**[AC]: Author's comment**

*The paper presents a thorough characterization of the observations mode of the EarthCARE CPR.*

*In particular it investigates the impact of the different modes on two aspect: 1) Doppler velocity errors , 2) occurrence of second-trip echoes. The paper is very important because it provides a description of the pros and cons associated to the different modes that have been, are and will be used at different latitudes and in different mission periods.*

*I have some major comments that I would like the authors address to make the paper more clear and concise.*

Thank you for the valuable comments that are greatly helpful to improve our manuscript. Our replies and corrections based on your comments are described below.

## Major comments

**[RC1]:** 1) The authors mention several times that they compute the standard deviation of Doppler velocity in several part of the paper. But this is left vague. The authors need to say across what ensemble such standard deviation is computed. This is very relevant in relation to the impact that what the authors refer to as "natural variability" std means. For instance if I understand correctly in Fig.4 the second row represent the std computed for each pixel in lat-height including all data with reflectivity between -20 dBZ and 0 dBZ (for 1 km Doppler velocities?). In that case the impact of the random component will be marginal (I expect) because in such a wide range of reflectivities there will be a large natural variability. In fact the authors do not present any quantitative intercomparison between the standard deviations of the different modes derived from Fig.4 (am I correct?). In fact I do not see the reason of plotting Fig.4 apart for documenting the behaviour of the mean Doppler velocity as a function of latitude and height (which by the way appears quite puzzling to me, why there are constant updrafts in the upper levels?). Also statement like in the conclusions (Line 395-397) are not very general since they are applicable to a given ensemble with the relative impact of the natural variability being very different from ensemble to ensemble.

**[AC1]:** Thank you for your valuable comment. We have clarified what ensemble such STD is computed. In Fig. 4, as the reviewer mentioned, the Doppler velocity STD was calculated from all 10-km integration Doppler velocity samples within each latitude–height bin using observations whose radar reflectivities ranged between –20 dBZ and 0 dBZ. We have added the following explanation:

- Lines 241–242 in the track-changed manuscript:  
“The standard deviation was calculated from all samples within each latitude–height bin for radar reflectivities between –20 dBZ and 0 dBZ. The 10-km integration Doppler data were used.”
- Line 265 in the track-changed manuscript:  
“The 10-km integration Doppler data were used.”

In addition, we agree that clarifying the integration length is important, as Doppler velocity STD strongly depends on it. Therefore, we have added the following sentences:

- Lines 152–153 in the track-changed manuscript:  
“Note that the difference between integration lengths of 1 km and 10 km affects the value of  $M$ , resulting in changes in  $\sigma_{\text{random}}$ .”
- Lines 274–275 in the track-changed manuscript:

“To investigate the dependence of STD on the integration length, results from 1-km and 10-km integrations are compared.”

Figure 3 has been revised so that theoretical calculations of Doppler velocity strongly depend on 1-km and 10-km integrations (Fig. R1). We have added the following sentence:

- Lines 173–174 in the track-changed manuscript:  
 “The 1-km and 10-km integrations are shown by dashed and solid lines, respectively.”

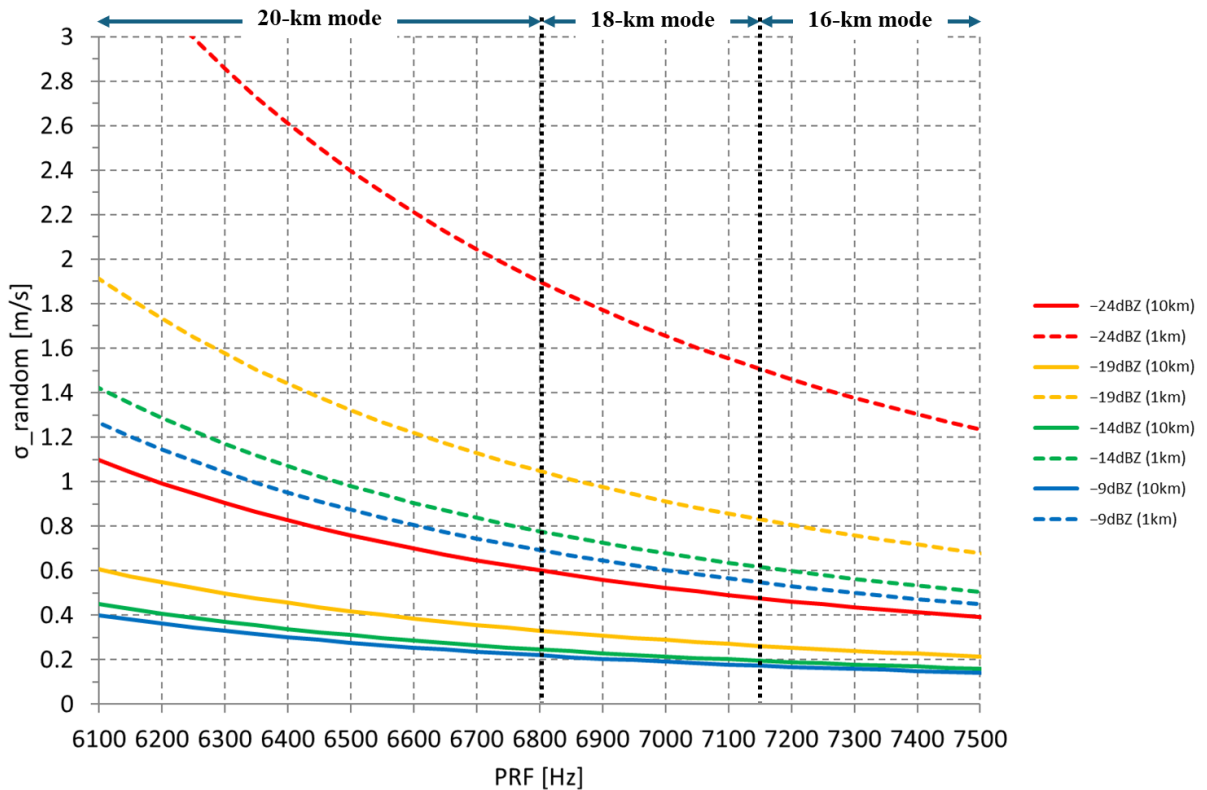


Figure R1: The theoretical relationship between PRF and  $\sigma_{random}$ , calculated using Eqs. (3) and (4) in the revised manuscript and the parameters listed in Table 1. The PRFs corresponding to the 20-km, 18-km, and 16-km modes are indicated at the top of the figure. The 1-km and 10-km integrations are shown by dashed and solid lines, respectively.

We also agree that the Doppler velocity STD shown in Fig. 4 includes substantial contributions from natural variability because the STD was calculated using all samples with reflectivities between  $-20$  dBZ and  $0$  dBZ. Therefore, Fig. 4 is intended primarily to provide a qualitative overview of the spatial distribution of Doppler velocity variability among the operational modes. This explanation has been added as follows:

- Lines 245–246 in the track-changed manuscript:

*“Figure 4 is intended primarily to provide a qualitative overview of the spatial distribution of Doppler velocity variability among the operational modes.”*

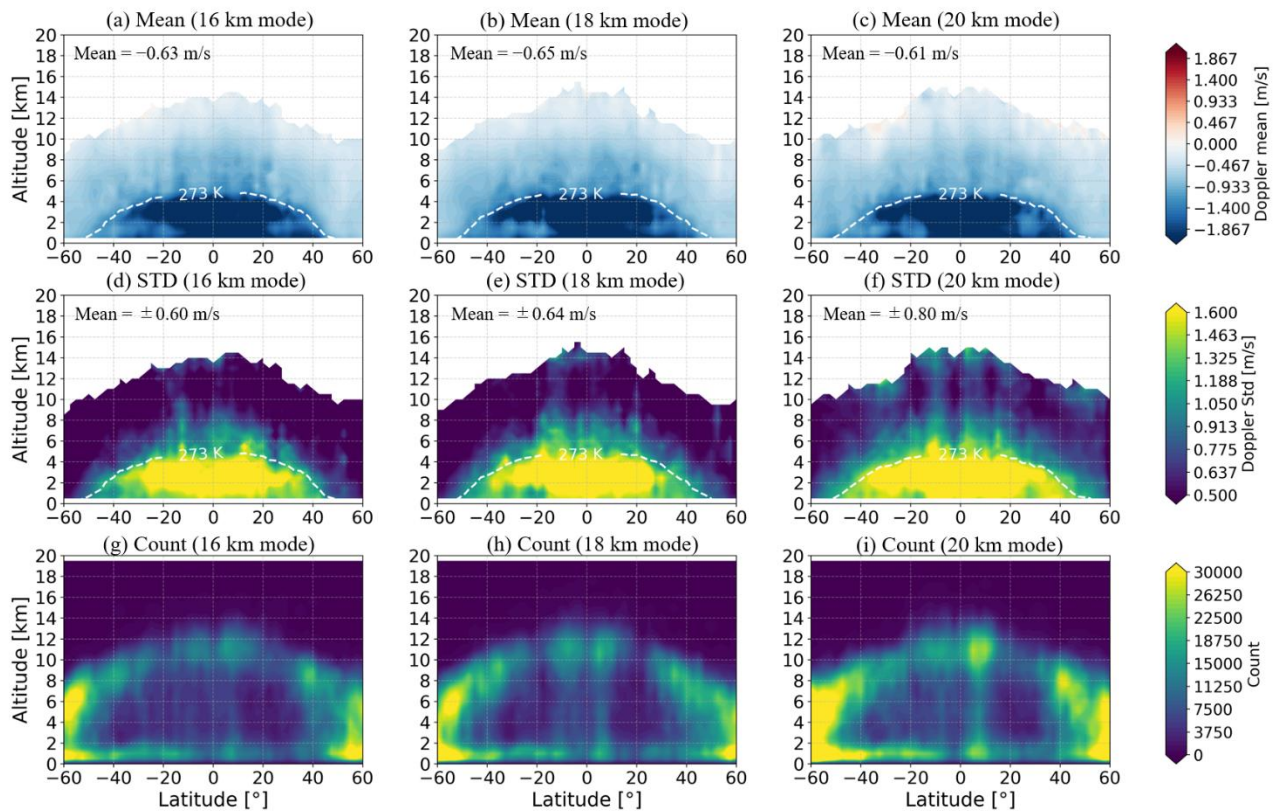
We additionally included the mean STD values at temperatures below 273 K in the revised Fig. 4 (Fig. R2), which shows that the 20-km mode tends to exhibit larger overall STD values than the 16-km and 18-km modes even under substantial natural variability. To improve visibility, the color scheme of the contour plots has been revised. We have added quantitative values to the manuscript:

- Lines 256–258 in the track-changed manuscript:  
*“... in cloud regions at temperatures below 273 K, the 20-km mode exhibits relatively large STDs (Fig. 4f; mean STD of  $0.80 \text{ m s}^{-1}$ ), whereas the 16-km and 18-km modes (Figs. 4d and 4e; mean STDs of  $0.60 \text{ m s}^{-1}$  and  $0.64 \text{ m s}^{-1}$ , respectively)...”*
- Lines 265–266 in the track-changed manuscript:  
*“The mean values of Doppler velocity and its standard deviation at temperatures below 273 K are shown at the top of each panel.”*

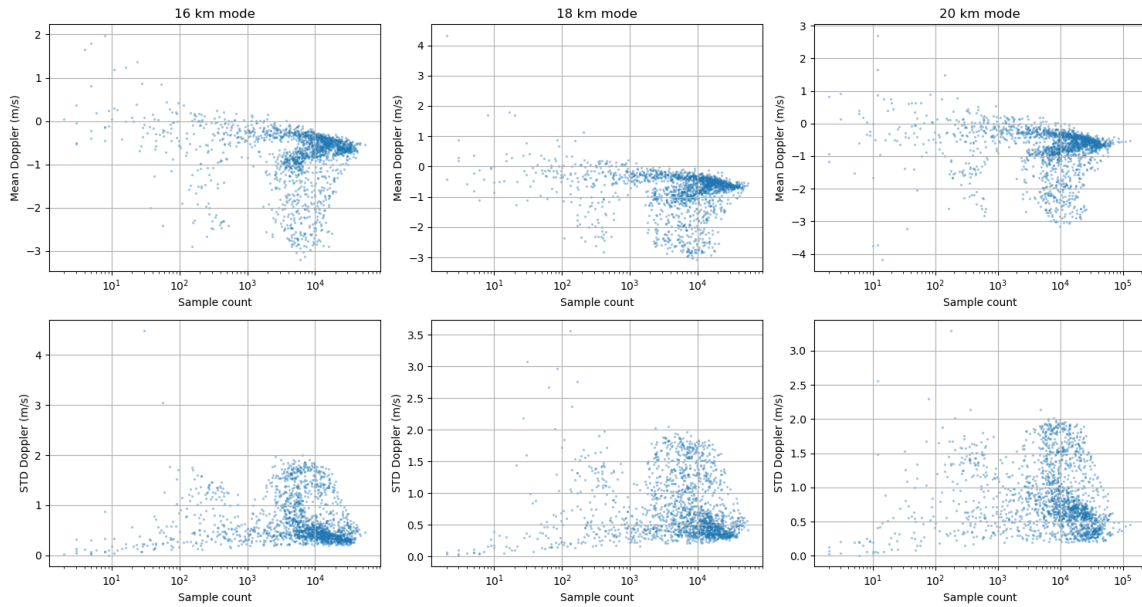
The mean STDs in the revised Figs. R2d–R2f show consistent results, confirming that the largest STD values are found in the 20-km mode, whereas the 16-km and 18-km modes exhibit smaller and comparable STDs. However, to more quantitatively evaluate PRF- and Z-dependent differences in Doppler measurement performance, we further analyzed the reflectivity dependence of Doppler velocity STD using narrower (5-dBZ) reflectivity bins in Figs. 5 and 6. These analyses reduce the influence of differing cloud regimes and demonstrate that the 20-km mode systematically exhibits larger STD values than the 16-km and 18-km modes across comparable reflectivity ranges.

Regarding the apparent presence of constant updrafts in the upper troposphere, we modified the color scale so that updrafts are represented in red (Figs. R2a–R2c). Furthermore, the mean Doppler velocity and STD were masked where the sample count was less than 1000 to exclude noisy Doppler velocity values associated with small sample sizes near cloud-top edges. The threshold of 1000 was determined based on Fig. R3, which shows the dependence of the mean and STD of Doppler velocity on sample count. This figure indicates that noisy Doppler velocity values characterized by large positive or negative means and large STDs are prevalent when the sample count is below 1000 but are substantially reduced for larger sample sizes. With the updated Fig. 4, it is now evident that widespread updrafts in the upper troposphere are less widespread. The following sentences were added:

- Lines 249–250 in the track-changed manuscript:  
*“In addition, the mean and STD of Doppler velocity were masked where the sample count was less than 1000 to exclude noisy Doppler velocity values associated with small sample sizes near cloud-top edges.”*
- Lines 269–270 in the track-changed manuscript:  
*“The mean Doppler velocity and STD are masked where the sample count is less than 1000.”*



**Figure R2:** Latitude-altitude cross sections of (a–c) mean Doppler velocity, (d–f) standard deviation of Doppler velocity, and (g–i) cloud sample counts for radar reflectivities between  $-20$  dBZ and  $0$  dBZ. The 10-km integration Doppler data were used. The mean values of Doppler velocity and its standard deviation above the 273 K isotherm are shown at the top of each panel. The 16-km, 18-km, and 20-km modes are shown from left to right. The white dashed line in panels (a–f) indicates the 273.15 K isotherm. Data acquired from 1 to 12 November 2024 were used, and only latitudes within  $60^{\circ}\text{S}$ – $60^{\circ}\text{N}$  are shown. Cloud echoes above the cloud-top heights detected by ATLID were excluded from the analysis. The mean Doppler velocity and STD are masked where the sample count is less than 1000.



**Figure R3: Scatter plot showing the dependency of mean (upper panels) and STD (bottom panels) of Doppler velocity on sample count in Fig. 4 in the manuscript.**

We agree that the relative contribution of natural variability depends on the analyzed cloud ensemble. To clarify this point and generalize the discussion, we have added the following statement:

- Lines 465–466 in the track-changed manuscript:  
*“Under the conditions considered in this study, the  $RD_{18km}$  is smaller than  $RD_{20km}$  (Fig. 5).”*

**[RC2]:** 2) Fig3 and Fig.5: Instead of plotting Fig.3 like it is it would be much better to merge Fig.3 in the top panel of Fig.5 (accounting for the integration length of course). For Fig.5 it would be good again to specify across which domain the std is taken. The intercomparison between the two curves will indeed explain what is the natural variability component (which should be kind of independent from the PRF but should depend on the integration length). It would be good to see some attempt to separate the impact of the random component (to verify whether it follows the expected behaviour).

**[AC2]:** Thank you for your comments on separation of Doppler velocity components. First, Fig. 3 is retained to show the theoretical discussion on the dependence of Doppler measurement performance on S/N ratio, PRF, and integration length, serving as an introduction to subsequent results based on actual observational data. We have included the theoretical values for both 1-km and 10-km integrations, considering the importance

of differences in integration length, as indicated in your previous comments. The theoretical random error is shown to decrease with increasing dBZ (S/N ratio), increasing PRF, and increasing integration length.

Next, we have revised Figs. 5a and 5b by overlaying the theoretical limits of random error in Doppler velocity measurements for each operational mode (Figs. R4a and R4b). In the theoretical calculations, we used the mean PRF values within the variable PRF ranges for each mode:

- Lines 290–292 in the track-changed manuscript:  
*“Dashed lines show the theoretical calculation of Doppler velocity measurement, derived from Eq. (3) following Doviak and Zrnic (1993). For these theoretical calculations, the PRF was set to 7,350 Hz, 7,000 Hz, and 6,300 Hz for the 16-km, 18-km, and 20-km modes, respectively, corresponding to the mean values within the variable PRF ranges for each mode.”*

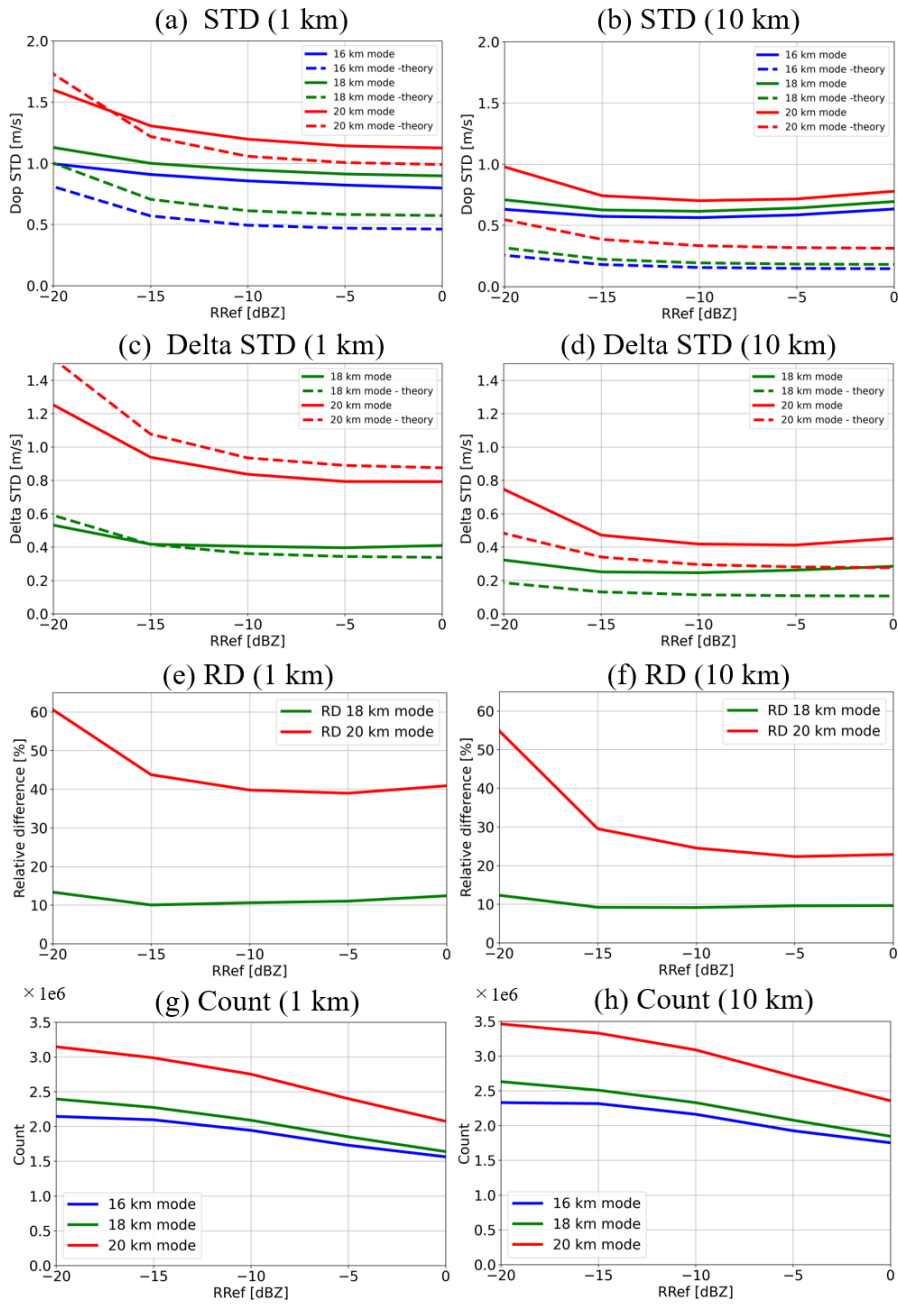
We have also specified which domain the STD is taken in the observation data as follows:

- Lines 275–279 in the track-changed manuscript:  
*“This analysis focuses on the latitudinal band from 60°S to 60°N during the special operation of the CPR from 1 to 12 November 2024. ...The standard deviation was calculated from all samples within each reflectivity bin between –20 dBZ and 0 dBZ and at temperatures below 273 K. ...”*

Compared with the theoretical random errors, the observed Doppler velocity STDs show behavior that is consistent with the theoretical values in terms of their decrease with increasing radar reflectivity (S/N ratio), increasing PRF, and increasing integration length. However, they are generally larger than theoretical value because the observed STDs include not only random measurement error but also contributions from natural variability. In addition, the use of SPU-A, which represents poorer Doppler measurement performance, also contributes to the larger observed values. One exception is found at –20 dBZ for the 1-km integration, where the theoretical value slightly exceeds the observed STD. This may be due to the use of a fixed PRF in the theoretical calculation, whereas the actual PRF varies with latitude. We have added the above discussion as follows:

- Lines 292–299 in the track-changed manuscript:  
*“The findings from Figs. 5a and 5b are fully consistent with the theoretical estimates of random Doppler velocity error; however, when focusing on the*

*absolute STD values, the observed STD is generally larger than the theoretical value. This is because the observed Doppler velocity contains not only random measurement error but also components associated with natural variability. In addition, the use of SPU-A, which represents poorer Doppler velocity measurement performance compared to SPU-B, also contributes to the larger observed STD. One exception is found at -20 dBZ for the 1-km integration, where the theoretical value slightly exceeds the observed Doppler velocity STD. This may be attributable to the use of fixed PRF value in the theoretical calculation, whereas the actual PRF varies with latitude.”*



**Figure R4:** (a, b) STDs of Doppler velocity ( $\text{m s}^{-1}$ ) as a function of radar reflectivity; (c, d) STD differences and (e, f) relative differences (%) of the 18-km and 20-km modes relative to the 16-km mode; and (g, h) sample counts for each radar reflectivity bin. The left and right panels correspond to the 1-km and 10-km integrations, respectively. The 16-km, 18-km, and 20-km modes are indicated by blue, green, and red lines, respectively. In panels (a)–(d), the solid and dashed lines represent observed values and theoretical estimates, respectively. The observed data from 1–12 November 2024 were used, and the analysis region is limited to latitudes within  $60^\circ$  and temperatures below 273 K. To ensure a consistent comparison among the modes, only clouds below 16 km were analyzed.

Regarding the decomposition of Doppler velocity errors, we have considered that Figs. R4c–R4f, which present inter-mode differences in random error under comparable ranges of natural variability for each reflectivity bin, provide useful insights. This approach seems particularly valuable because the theoretical formulation of Doviak and Zrnic (1993) does not fully reproduce the observed random errors of CPR.

The  $\Delta$ STDs used in Figs. R4c and R4d effectively remove the contribution of natural variability under the assumption that the natural variability component is common among the modes within each reflectivity bin, implying that they can be directly compared with the theoretical random error estimates. Therefore, we have added the theoretical differences in Doppler velocity random error among the modes, shown as dashed lines in Figs. R4c and R4d. The theoretical and observed  $\Delta$ STDs are in good agreement, both exhibiting decreasing trends with increasing radar reflectivity, and the 20-km mode consistently shows larger values than the 18-km mode.

In contrast, the RDs in Figs. R4e and R4f do not effectively remove the natural variability component, therefore, theoretical values are not shown. Instead, they provide a normalized measure of the relative differences in Doppler STD with respect to the 16-km mode. As such, the RDs highlight the relative magnitude of the degradation in Doppler measurement performance among the modes, regardless of the absolute STD values. We have added the above discussion as follows:

- Lines 335–341 in the track-changed manuscript:  
*“In addition, the theoretical differences in STDs shown in Figs. 5c–5d are in good agreement with the observations, both exhibiting decreasing trends with increasing reflectivity, and the 20-km mode consistently shows larger values than the 18-km mode. In particular, the theoretical and observed STD differences show very close agreement for the 18-km mode at the 1-km integration. The slight discrepancies between the observed and theoretical values likely arise from the aforementioned use of SPU-A, the use of a fixed PRF, and the possibility that the natural variability component is not completely removed.”*

**[RC3]:** 3) I am not so sure Fig.6 adds much on what already shown in Fig.5.

**[AC3]:** Thank you for your comment. We agree that Fig. 6 does not provide substantial additional information beyond what is already shown in Fig. 5. As our main conclusions are fully supported by Fig. 5, we have removed Fig. 6 from the manuscript.

**[RC4]:** 4) terminology: instead of using "mirror" frequency and similar expression I would use "second-trip echoes" frequency because the origin can actually be different (not necessarily mirror images)

**[AC4]:** Thank you for your comment. The terminology related to “mirror images” has been changed to “second-trip echo” throughout the manuscript.

**[RC5]:** 5) "Cloud overlap risk" in Sect 3.5 : I would highlight caveats to the proposed definition. Indeed using a product of probabilities is correct if the two events are independent (which I would not say is the case).

**[AC5]:** Thank you for your comment. The authors agree that the cloud and mirror occurrences are not statistically independent, and therefore their product does not represent a true joint probability. Instead, we introduced the cloud overlap risk only as an index to highlight altitudes where both cloud occurrence and mirror occurrence are frequent. This caveat has been added as follows:

➤ Lines 413–418 in the track-changed manuscript:

*“Note that this metric is not intended to represent the true joint probability of second-trip echoes and cloud occurrence, because the two events are not statistically independent. Specifically, as cloud-top heights increase, the altitude at which second-trip echoes from mirror images appear becomes lower, leading to a higher likelihood of overlap with actual cloud echoes when high clouds are present. MS tails also tend to occur in association with deep convection, in which case second-trip echoes are likewise more likely to overlap with real cloud echoes. Rather, it is introduced as a risk index that combines the occurrence frequencies of real clouds and second-trip contamination.”*

#### **Minor comments:**

**[RC6]:** 1) Fig 9, last row. Cloud and mirror overlap = is this the same as cloud overlap risk? Then use the same name

**[AC6]:** Thank you for your comment. The term “cloud and mirror overlap” corresponds to “cloud overlap risk.” We have revised Fig. 8 in the track-changed manuscript to use consistent terminology.

**[RC7]:** 2) Eq.3: why are you introducing  $C$  ( $C=1$  in Table 1) I would delete  $C$  from the Equation and the Table.

**[AC7]:** The authors agree with the reviewer's comment. Accordingly, the  $C$  has been removed from the manuscript (Lines 150–151 in the track-changed manuscript).

**[RC8]:** 3) Table 1:  $\sigma_{sm}$ : in the third column there is an expression that is correct for  $\sigma_{sm}$  not the square of it. Also not clear to me what values of  $V_s$  is used

**[AC8]:** As the reviewer pointed out, the expression in the third column corresponds to  $\sigma_{sm}$  itself, not its square. This has been corrected in the revised manuscript. In addition,  $\sigma_v$  had been expressed as its squared value, and has therefore been corrected to its square root.  $V_s$  denotes the ground track speed of the satellite (7,738 m/s), which is already specified in Table 1.

**[RC9]:** 4) Line 188: this is due to pulse stretching as documented in Xu et al., 2025 <https://doi.org/10.5194/egusphere-2025-5421>

**[AC9]:** Thank you for providing this valuable information. We have added a description of pulse stretching in the revised manuscript as follows:

- Lines 196–198 in the track-changed manuscript:  
*“This tendency can be attributed to pulse stretching effects inherent in radar observations, which can lead to an overestimation of cloud top heights by CloudSat, as discussed in Xu et al. (2025).”*