

Response to comments by referee #1

Shunsuke Aoki, Takuji Kubota, Hiroaki Horie, and Yuichi Ohno: “Characteristics of multiple-trip echoes observed by EarthCARE Cloud Profiling Radar”, submitted to Atmospheric Measurement Techniques (AMT) (egusphere-2026-3256).

RC1: 'Comment on egusphere-2026-3256', Anonymous Referee #1, 01 Jul 2026

This paper provides a clear and comprehensive description of second- and multiple-trip echoes in EarthCARE observations. It proposes practical methods to identify and screen these echoes while thoroughly characterizing their vertical and zonal distributions. Very interesting to see also the discussion about the satellite mirror, the first time this is seen in cloud spaceborne radars. Overall, the manuscript is very well written, with clear figures, a logical structure, and well-supported arguments. I have only a few minor comments that I believe would further improve the paper.

The authors sincerely thank the reviewer for carefully reading the manuscript and for providing constructive feedback. We also appreciate the reviewer's recognition of the value of our study. We have carefully reviewed the manuscript in response to the reviewer's comments. My point-by-point responses are provided below in red. Please note that the line numbers indicated in our responses refer to the revised manuscript.

1) Figure 1 and explanation of SMI height

In Figure 1, the term nR_u appears, but the parameter n is not defined. Please clarify its meaning in either the figure or the caption. In addition, in Lines 215–218 you explain why, over ocean surfaces, the SMIs consistently appear near $H_{SMI} = 2.4$ km regardless of the pulse repetition frequency (PRF). Since this is not immediately intuitive, especially for readers who are not familiar with radar principles, I think a simple timing diagram (chronogram) would be very helpful to illustrate this behavior.

Thank you for pointing this out. We agree that the meaning of n was not defined clearly. We have therefore added the following explanation to the caption of Fig. 1:

Line 69

R_u is the unambiguous range and n is the number of pulse-repetition intervals separating the nominal reception timing from the reception window in which the multiple-trip echo from SMI is detected, typically ranging from 17 to 20.

We also agree that the persistence of SMIs near 2.4 km under the operationally varying PRF is not intuitive. We have therefore added an explanation on that point in the revised manuscript with a timing diagram (Fig. 6) and PRF-variations in one orbit (Fig. 5):

Line 251–262

When the surface is at sea level, SMIs appear persistently near $H_{SMI} = 2.4$ km. This is because the PRF is controlled as a function of satellite altitude to ensure the required vertical observation range (Imura et al., 2026). Figures 5a and 5b shows the variations in PRF and H_{sat} over one orbit. Even within the same observation mode, the PRF varies with H_{sat} .

Figure 6 shows a radar timing diagram of the radar transmission and reception windows, together with the received pulses from the surface and the SMI. Transmission and reception windows alternate, and successive pulses are transmitted in the intervals of PRI before the return from the first transmitted pulse is received. The PRI is controlled according to H_{sat} so that the return from Earth's ellipsoid ($H_{sfc} = 0$) is always received Δt ($\approx 16 \mu s$) before the next pulse transmission. The corresponding round-trip travel time, ΔT , therefore satisfies

$$\Delta T = \frac{2H_{sat}}{c} = n \cdot PRI - \Delta t, \quad (7)$$

where n is a positive integer typically ranging from 17 to 20. The SMI pulse travels twice the path length of the first-trip surface echo and is therefore received after a travel time of $2\Delta T$. Consequently, after the 34th reception timing in this example, the SMI pulse is received Δt earlier than the surface echo from the 18th transmitted pulse. This timing difference corresponds to an apparent altitude of $c\Delta t/2 \approx 2.4$ km, explaining why the SMI consistently appears near this altitude.

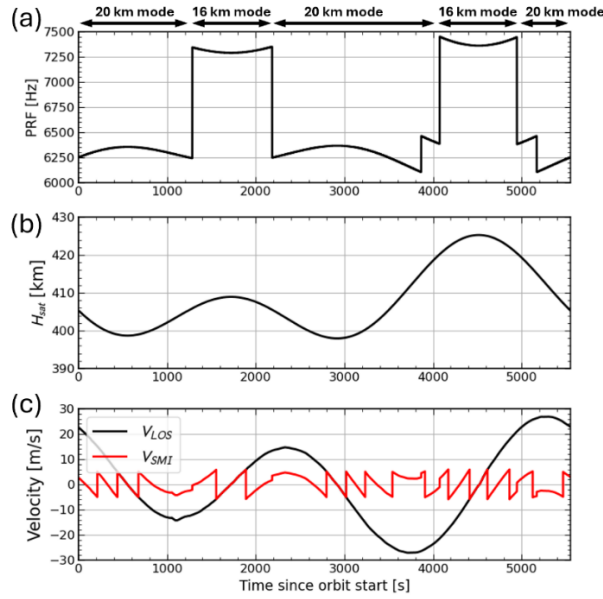


Figure 5: (a) PRF; (b) H_{sat} ; and (c) V_{LOS} and expected V_{SMI} calculated assuming $V_{sfc} = 0$ during one orbit of orbit number 06198 on 1 July 2025.

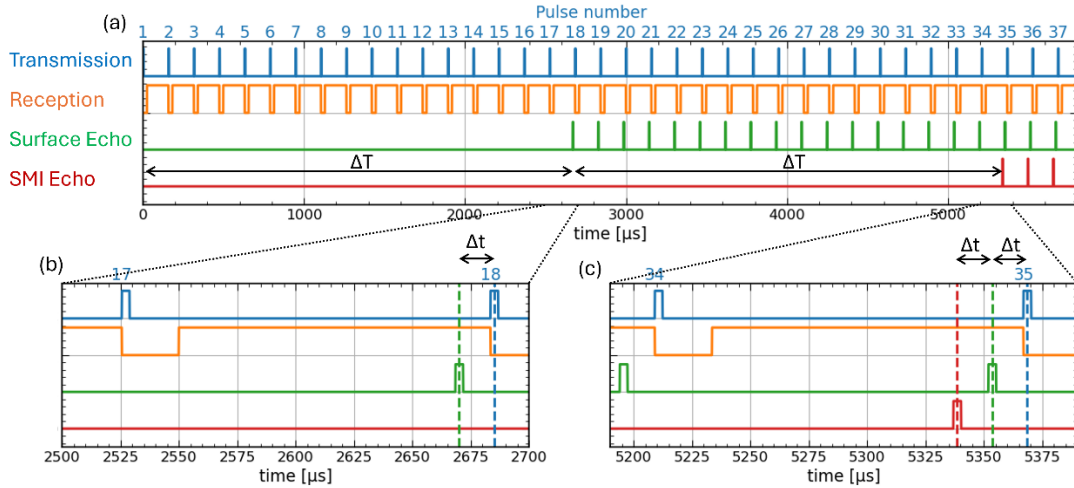


Figure 6: Timing diagrams of the radar transmission and reception windows, together with the received pulses from the surface and the SMI, for an example in the 20 km mode at a satellite altitude of approximately 400 km.

2) Line 23, The phrase "surfaces with near-saturated backscatter" is somewhat vague for readers who are not familiar with Cloud Profiling Radar (CPR) observations. It would be helpful to provide a more quantitative description, for example by indicating an approximate σ^0 threshold corresponding to near-saturated backscatter.

We agree that the original wording may not have been sufficiently clear to readers who are less familiar with the CPR and was therefore too vague for the abstract. Figure 15 (previous Figure 11) shows that SMIs occur frequently when exceeds approximately 25 dB, while the additional discussion in Sect. 5.4 provides evidence that these echoes are associated with specular reflection at surface. We have therefore revised the sentence as follows:

Line 21

In contrast, SMIs occur almost exclusively over surfaces with specular reflection, where the normalized radar cross section is larger than approximately 25 dB, such as melting sea ice and land with surface-water cover.

We also identified a similar, potentially unclear expression in Sect. 6 and revised it accordingly.

Line 681–686

SMIs exhibit a distinct dependence on surface properties, occurring only for σ^0 values above approximately 25 dB, approaching the CPR receiver saturation level of approximately 30 dB. Their occurrence is strongly concentrated over sea ice affected by summer surface melting and over land with surface-water cover. Analysis of the special observation period with slightly off-nadir pointing showed that SMIs occurred only when the incidence angle relative to the local surface was smaller than approximately half of the CPR beamwidth, supporting the interpretation that their occurrence is associated with specular reflection at surface.

3) Figure 13: I suggest placing slightly more emphasis on the feature shown in Figure 13e over the tropical region. The persistence of reflectivities around -20 dBZ near cloud top, rather than decreasing toward the CPR sensitivity limit, appears to be a clear indication that second-trip echoes have not been completely eliminated or separated from the genuine cloud signal. Have the authors considered subtracting the extrapolated multiple-scattering tail from the observations? It would be interesting to assess whether such a correction recovers a more expected behavior in the figure.

Thank you for this insightful comment. To investigate whether the anomalously large reflectivity in the tropical upper troposphere is caused by residual second-trip echoes, we performed a complementary analysis using CloudSat observations. Contrary to our initial expectation, CloudSat, for which second-trip contamination is not expected within the observed altitude range, shows a similar feature. As shown in Fig. 16s, the mean reflectivity over the tropics does not decrease toward the radar sensitivity limit near cloud top but instead remains relatively high, approaching -15 dBZ. This comparison suggests that the feature in Fig. 17e (previous Fig. 13e) cannot be attributed solely to residual second-trip echoes. Rather, it may primarily reflect the transport of relatively large ice particles into the upper troposphere by deep convective systems extending to altitudes of 15–17 km in the tropics.

Nevertheless, we agree that treating cases in which second-trip echoes overlap genuine cloud signals is important for EarthCARE/CPR cloud observations. We considered the suggested subtraction of the extrapolated multiple-scattering tail. However, as shown in new Fig. 3, the estimated reflectivities of mirror images and MS tails currently involve substantial uncertainties. Directly subtracting these estimates from the observed power would not provide a sufficiently robust correction. We consequently consider the development and validation of such a correction to be beyond the scope of the present study, but an important subject for future work. We have added the CloudSat comparison and the above discussion to the revised manuscript as follows:

Line 566–587

Figures 17r and 17s show the cloud echo fraction and mean reflectivity observed by CloudSat, averaged over the corresponding months from 2007 to 2010. They are closely consistent with those from EarthCARE/CPR (Figs. 17d and 17e), indicating that statistical properties of cloud can be reasonably reproduced when second-trip echoes are properly removed. The more frequent echo occurrence and lower mean reflectivity observed by EarthCARE compared with CloudSat are consistent with the higher sensitivity of EarthCARE/CPR, whose minimum designed detectable reflectivity is approximately -35 dBZ, compared with approximately -29 dBZ for CloudSat.

Above 15 km in the tropics, the mean reflectivity is anomalously large, reaching approximately -15 dBZ compared with that at midlatitudes in both Figs. 17e and 17s. This may be because, in deep convective systems extending to altitudes of 15–17 km in the tropics, relatively large ice particles are transported into the upper troposphere, resulting in enhanced radar reflectivity at these altitudes (Field et al. 2007; Yuan et al. 2011). For EarthCARE, however, the contribution of second-trip echoes cannot be completely excluded. In overlapping cases, the power of second-trip echoes may be superimposed on genuine cloud echoes, or weak cloud-top echoes may be masked by second-trip echoes, causing only relatively strong echoes to be identified as clouds. As shown in Fig. 3, the estimated reflectivity of second-trip echoes still involves considerable uncertainty. Further improvement in the estimation of second-trip echo and subtraction of its contribution from the observed reflectivity would therefore be desirable for better treatment of such overlapping cases.

Reference

Field, P. R., Heymsfield, A. J., and Bansemer, A.: Snow Size Distribution Parameterization for Midlatitude and Tropical Ice Clouds. *J. Atmos. Sci.*, 64, 4346–4365, <https://doi.org/10.1175/2007JAS2344.1>, 2007.

Yuan, J., Houze, R. A., and Heymsfield, A. J.: Vertical Structures of Anvil Clouds of Tropical Mesoscale Convective Systems Observed by CloudSat. *J. Atmos. Sci.*, 68, 1653–1674, <https://doi.org/10.1175/2011JAS3687.1>, 2011.

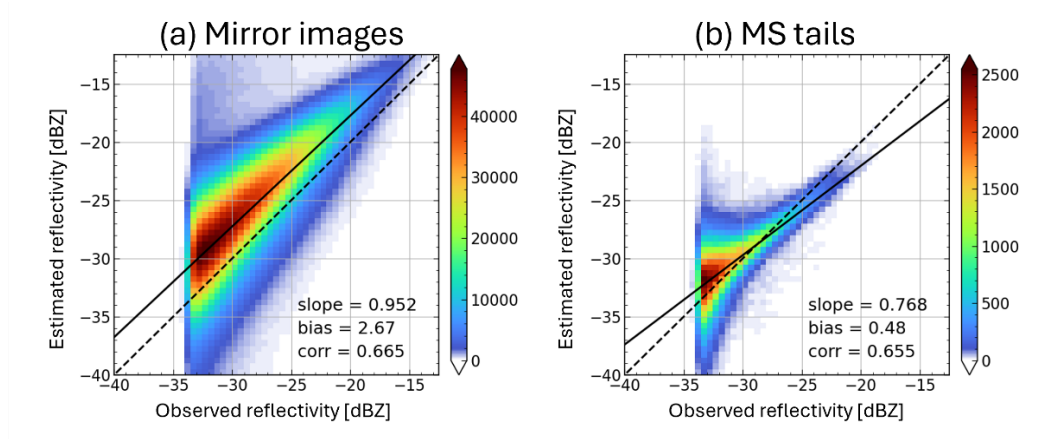


Figure 3: Joint histograms of observed and estimated radar reflectivity factor for echoes classified as certain (a) mirror images and (b) MS tails during 2025.

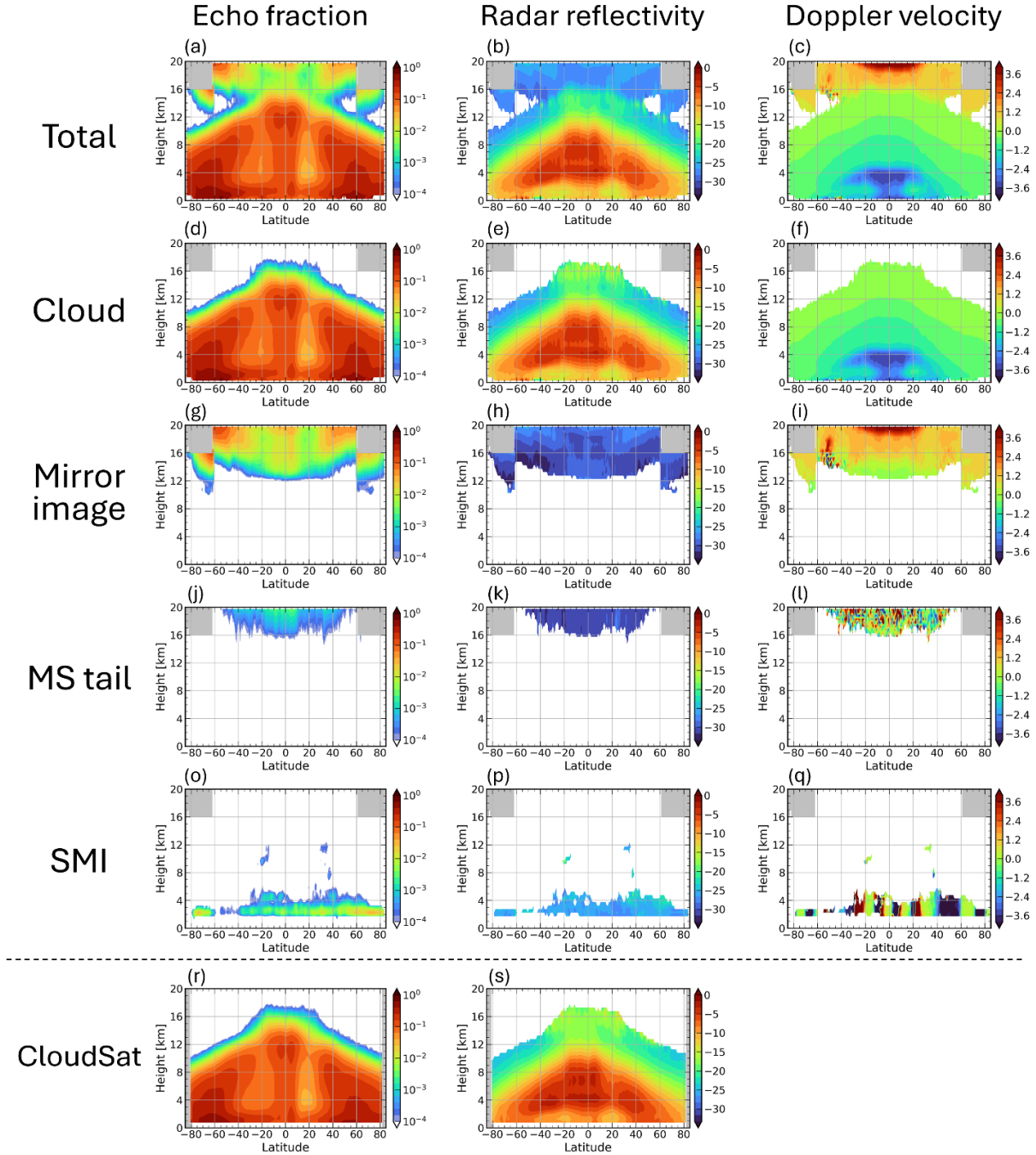


Figure 17: (a–q) Zonal-mean height distributions of echo occurrence frequency, mean radar reflectivity factor, and mean Doppler velocity for each echo category, namely all echoes, clouds, mirror images, MS tails, and SMIs observed by EarthCARE/CPR, averaged over the 7-month period from December 2024 to June 2025. (r, s) Zonal-mean height distributions of echo occurrence frequency and mean radar reflectivity factor observed by CloudSat averaged over the corresponding months from 2007 to 2010.