

Response to comments by referee #2

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).

RC2: 'Comment on egusphere-2026-3256', Anonymous Referee #2, 25 Jul 2026

This manuscript describes various type of range-ambiguous signal that can affect the EarthCare Cloud Profiling Radar (CPR) data. The authors categorize these signals into three different types: mirror image and multiple scattering, which have been seen previously, as well as the satellite mirror image (SMI). When I was first reading about the SMI, I was somewhat skeptical that the satellite backscatter could be large enough to still be detectable after another round trip to earth's surface. However, the evidence presented seems convincing; I do have a couple of questions listed below. In general, the paper is well-written and provides important characteristics for each of the ambiguous sign types. I think it can be of strong interest to users of the EarthCare CPR data. I have some specific comments below.

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. In particular, we have expanded the discussion of SMI echo-power estimation and its dependence on incidence angle, and clarified the procedure used to identify mirror images. 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.

Line 44: “widow” -> “window

Thank you for pointing this out. We revised the manuscript accordingly.

Line 75 – regarding the SMI, have the authors tried to estimate the SMI signal strength by assuming some reasonable radar cross section for the satellite?

Thank you for this important comment. In principle, the received power of an SMI echo can be estimated from the radar equation by treating the effective radar cross section of spacecraft σ_{sat} and effective reflection factor at surface R_{sfc} . However, both σ_{sat} and R_{sfc} are poorly constrained, making a reliable quantitative prediction of the SMI signal level difficult. We have added the following discussion to the revised manuscript:

Line 291–303

3.3.2 Estimation of Z and V for SMIs

In principle, the received power of an SMI echo can be estimated from the radar equation by treating the spacecraft as an effective point target observed through two specular surface reflections:

$$P_{r,SMI} = \frac{P_t G^2 \lambda^2 \sigma_{sat}}{(4\pi)^3 [2(H_{sat} - H_{sfc})]^4} R_{sfc}^2 10^{-4A_{atm}/10}, \quad (8)$$

where P_t is transmitted power, G is the CPR antenna gain at boresight, λ is the wavelength of the radio wave, σ_{sat} is the effective radar cross section of the spacecraft, R_{sfc} is the effective surface reflection factor, and A_{atm} is the one-way path integrated attenuation. Although R_{sfc} could be constrained from the first-trip surface echo, this is difficult because the receiver is typically saturated, as indicated by the measured σ^0 leveling off at approximately 30 dB (Figs. 4b and 7b). One possible contribution to σ_{sat} is structural scattering from the electrically large 2.5 m reflector and other spacecraft components. Another possible contribution is antenna-mode scattering, in which part of the power received by the antenna is reflected at impedance mismatches in the feed system and subsequently reradiated (Munk, 2003; Shrestha et al., 2009). However, the radar cross sections associated with both structural scattering and antenna-mode scattering are unknown, making a more quantitative estimate difficult.

References

Munk, B. A.: Finite Antenna Arrays and FSS, John Wiley & Sons, Hoboken, New Jersey, USA, <https://doi.org/10.1002/0471457531>, 2003.
Shrestha, S., Balachandran, M. D., Agarwal, M., Zou, L.-H., and Varahramyan, K.: A method to measure radar cross section parameters of antennas, IEEE T. Antenn. Propag., 56, 3494–3500, <https://doi.org/10.1109/TAP.2008.2005541>, 2008.

Also, was CPR ever operated prior to establishing exact nadir pointing, which would preclude SMI, as the authors note (line 78)? See also comment on line 216.

During a one-day period from 15 to 16 November 2024, covering 16 orbits (frames 02652G–02668F), a special operation referred to as the “Zero Doppler” observation was conducted. This operation was designed to minimize V_{LOS} , but consequently caused the beam direction to deviate from the exact nadir pointing. We therefore examined whether the occurrence of SMIs was reduced during this special observation mode, demonstrating that the occurrence frequency of SMIs is clearly lower during the Zero Doppler observations than during the nominal observations. These findings provide further evidence that SMIs are produced by a two-round-trip propagation path involving specular reflection of the radar beam at the surface. We have added these results in the new Sect. 5.4.1 as follows:

Line 608–625

5.4.1 Zero Doppler observation of EarthCARE/CPR

If the occurrence of SMI echoes is indeed associated with specular reflection at the surface, even a slight off-nadir pointing of the CPR beam should suppress their occurrence. During a one-day period from 15 to 16 November 2024, covering 16 orbits (frames 02652G–02668F), a special operation referred to as the “Zero Doppler” observation was conducted. In this mode, the spacecraft attitude was controlled so that the CPR beam remained perpendicular to the satellite velocity vector. This operation was designed to minimize V_{LOS} , but consequently caused the beam direction to deviate from the local surface normal. We therefore examined whether the occurrence of SMIs was reduced during this period.

Figures 18a and 18d show global maps of SMI occurrence frequency during the Zero Doppler observations and during the subsequent 16 nominal orbits (frames 02668G–02684F), respectively. The occurrence frequency of SMIs is clearly

lower during the Zero Doppler observations than during the nominal observations. Figures 18b and 18e show maps of the CPR beam incidence angle relative to the WGS84 Earth ellipsoid, averaged over the respective period, while Figs. 18c and 18f show their zonal mean values. Under nominal observations, the incidence angle is generally on the order of 0.01° , indicating the CPR beam is closely aligned with the local surface normal. In contrast, the incidence angle during the Zero Doppler observations exhibits a clear latitudinal dependence. The latitude bands in which SMIs are observed in Fig. 18a broadly correspond to regions where the incidence angle is smaller than approximately 0.05° – 0.1° . Since the 3-dB beamwidth of the CPR is approximately 0.095° , SMIs are expected to occur preferentially when the incidence angle is smaller than roughly half of the 3-dB beamwidth, or approximately 0.05° . The results shown in Fig. 18 are consistent with this expectation and provide further evidence supporting the proposed SMI-mechanism.

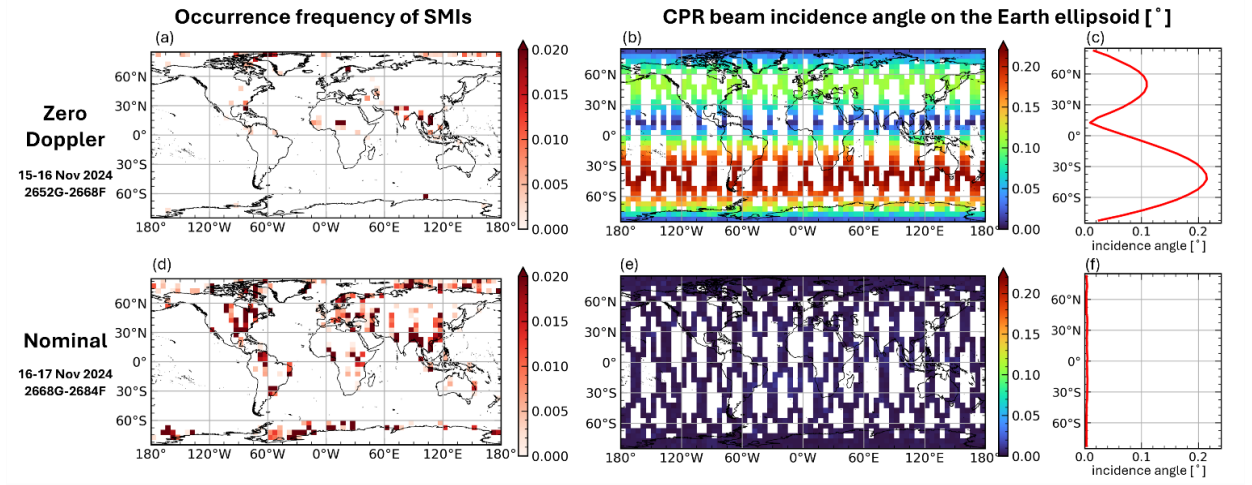


Figure 18: Maps of (a, d) SMI occurrence frequency and (b, e) CPR beam incidence angle on the Earth ellipsoid, together with (c, f) the zonal mean incidence angle, for the Zero Doppler observations (frame 02652G–02668F) and the subsequent nominal observations (frame 02668G–02864F).

In addition, the proposed SMI mechanism is not unique to EarthCARE/CPR. During an exact-nadir observation by CloudSat on 1 August 2006, apparent false echoes were detected at the altitude predicted from the PRF and satellite altitude. This independent example supports the applicability of the proposed mechanism to other nadir-pointing spaceborne radars under specular surface-reflection conditions. We have added this example in the new Sect. 5.4.2 as follows:

Line 632–643

5.4.2 CloudSat's nadir pointing observation

The occurrence conditions of SMIs discussed above suggest that similar echoes can also occur in other spaceborne radars. CloudSat conducted nadir-pointing observations with an incidence angle of 0° from 7 July to 15 August 2006. To avoid receiver saturation associated with specular surface reflection, the pointing direction was subsequently changed to 0.16° off nadir on 15 August 2006. Figure 19 shows a CloudSat observation over the Arctic Ocean on 1 August 2006, during the period of exact-nadir observations. An echo is observed near 5.5–6 km, indicated by the dashed line, where an SMI is expected to appear according to Eq. (6). At the same time, σ^0 reaches a plateau near 25 dB, suggesting that the receiver reached saturation due to specular reflection at surface. No corresponding signal is observed in the 532-nm backscatter measured by the CALIPSO lidar, confirming that the radar echo is spurious rather than a genuine cloud echo. Unlike for EarthCARE, the expected SMI altitude in CloudSat is not constant because its PRF is controlled differently from the scheme described in Eq. (7). These results confirm that SMIs are not unique to EarthCARE and can also occur in other nadir-pointing spaceborne radars when the condition for specular surface reflection is satisfied.

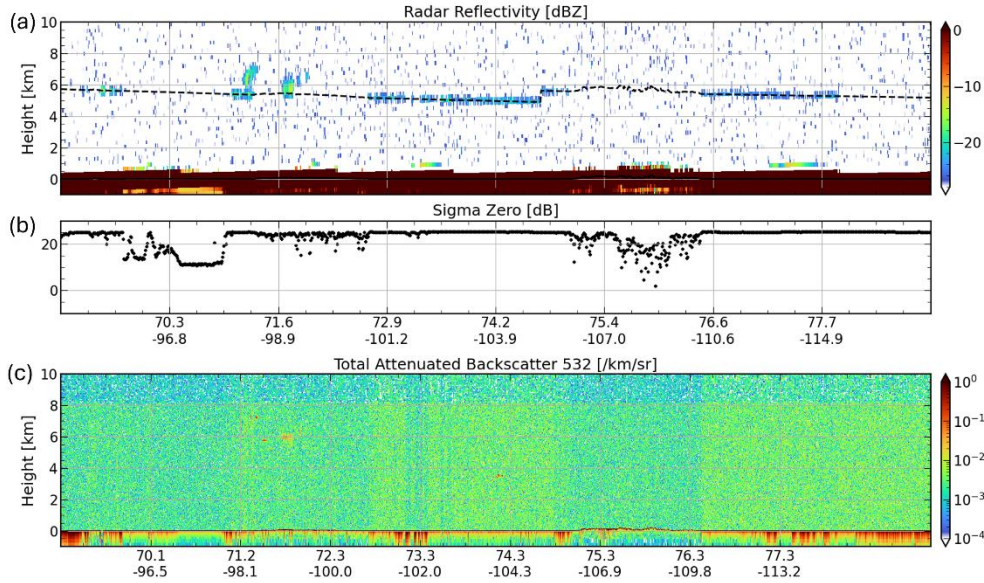


Figure 19: CloudSat (a) radar reflectivity factor and (b) σ^0 , together with (c) the CALIPSO lidar 532-nm attenuated backscatter coefficient, during CloudSat nadir observations on 1 August 2006 (orbit 01389).

Line 164 – The assumed k-Z relationship is for cirrus clouds. However, I'm assuming a large amount of the attenuation in Figure 2 comes from stratiform precipitation, which likely has a different k-Z relationship. How sensitive are the results to the assumed k-Z relationship?

Line 169 - My initial interpretation of (4) was that it is the level of a desired signal to the level of mirror image (like SNR). Hence, I was puzzled by the next comment, suggesting that SMR depends on the ability to estimate the MI return. It seems like (4) is more of an error measure of the deviation between the observed Z at a given height and the predicted Z_{MI} at that height. The algorithm identifies small SMR as mirror image. It seems like an observed Z well below the predicted Z_{MI} would also be identified as MI - could this result in the removal of real high-altitude Z? How accurate does the predicted Z_{MI} need to be?

Thank you for the two important comments regarding the estimation of the reflectivity factor of mirror images. As the reviewer correctly pointed out, the parameter in Eq. (4) depends on the accuracy of the estimated mirror-image reflectivity, and the term signal to mirror ratio (SMR) could therefore be misleading. We have replaced SMR with

$$\Delta Z_{MI}(h) \equiv Z_{MI}(h) - Z_{obs}(h).$$

and revised the relevant text accordingly. If the mirror-echo intensity at a given altitude could be estimated perfectly, ΔZ_{MI} would be 0 dB. By contrast, ΔZ_{MI} becomes negative when the observed echo includes a genuine cloud contribution or when the mirror-image echo is weaker than the background noise level. We now identify mirror images by applying a lower threshold, $\Delta Z_{MI}(h) > g(h)$.

The accuracy of Z_{MI} is important for this classification. The choice of the k-Z relationship and the use of attenuated Z to estimate attenuation may lead to an underestimation of attenuation and, consequently, an

overestimation of Z_{MI} . The estimated surface-reflection loss is also uncertain. To evaluate the performance of the estimation using actual CPR observations, we added a joint histogram of the observed and estimated mirror-image reflectivities in Fig. 3a. The slope of the linear regression is close to unity, indicating that the relative variations in echo intensity are well reproduced by the estimate. However, Z_{MI} has a positive bias of 2.67 dB, and most cases fall within the range $0 < \Delta Z_{\text{MI}} < 10$ dB.

We therefore impose no upper threshold on ΔZ_{MI} . This approach may cause weak genuine cloud echoes to be incorrectly classified as mirror images. Nevertheless, the analysis presented in Sect. 4 confirms that the criterion performs adequately in practice without substantially removing genuine cloud echoes near cloud top. We have incorporated the above discussion into the revised manuscript.

Line 183–208

For the identification of mirror echoes, we first calculated the difference between the observed and estimated Z , in dB, as

$$\Delta Z_{\text{MI}}(h) \equiv Z_{\text{MI}}(h) - Z_{\text{obs}}(h). \quad (4)$$

If the mirror-echo intensity at a given altitude could be estimated perfectly, ΔZ_{MI} would be 0 dB, and become negative when the observed echo includes a genuine cloud contribution or when the mirror-image echo is weaker than the background noise level. However, accurate prediction is challenging because of uncertainties in the hydrometeor attenuation, and a variety of scattering property depending on surface conditions (the third and fourth terms of Eq. (3)). We therefore flagged detected echoes at altitudes satisfying $\Delta Z_{\text{MI}}(h) > g(h)$ as likely mirror images. Here, $g(h)$ is an empirically determined altitude-dependent threshold chosen to decrease with height, reflecting the greater likelihood of mirror-image occurrence at higher altitudes. Two thresholds were introduced to indicate two confidence levels, “certain” and “possible”. In CPR_ECO version Cc, $g(h) = c_0 + (R_u - h)/1000$, where c_0 is a constant set to -20 for the “possible” category and -10 for the “certain” category. Over land, diffuse scattering from rough surfaces causes greater loss of the signal, which lead to an overestimation of Z_{MI} . To account for this effect, $g(h)$ is increased by 20 dB over land. Figure 2c shows the resulting classification, which successfully flags false echoes at high altitudes.

Figure 3a shows the joint histogram of Z_{obs} and Z_{MI} for echoes classified as “certain” mirror images by CPR_ECO during 2025. The slope of the linear regression is close to unity, indicating that the relative variations in echo intensity are well reproduced by the estimate. However, Z_{MI} has a positive bias of 2.67 dB, and most cases fall within approximately $0 < \Delta Z_{\text{MI}} < 10$ dB. This bias may be attributable to an underestimation of losses due to attenuation and surface reflection. For example, the empirical k – Z relationship for stratiform rain at W band is given by $k = 0.047Z^{0.94}$ (Fairall et al. 2018), indicating stronger attenuation than for cirrus clouds. Furthermore, the present calculation uses attenuated Z , resulting in an underestimation. In addition, the loss associated with surface reflection can also be larger than the assumed value because of surface roughness, vegetation, partial water coverage, and roughness of the water surface.

Applying the lower threshold on ΔZ_{MI} used in this study reduces the risk of misclassifying strong spurious echoes as genuine cloud echoes, which would be particularly problematic for subsequent cloud analysis. On the other hand, no upper threshold is imposed on ΔZ_{MI} , because Z_{MI} can be overestimated owing to the effects described above. Although this criterion may make weak genuine clouds to be incorrectly classified as mirror images, we confirmed that it does not result in excessive removal of true echoes near cloud top in Sect. 4.

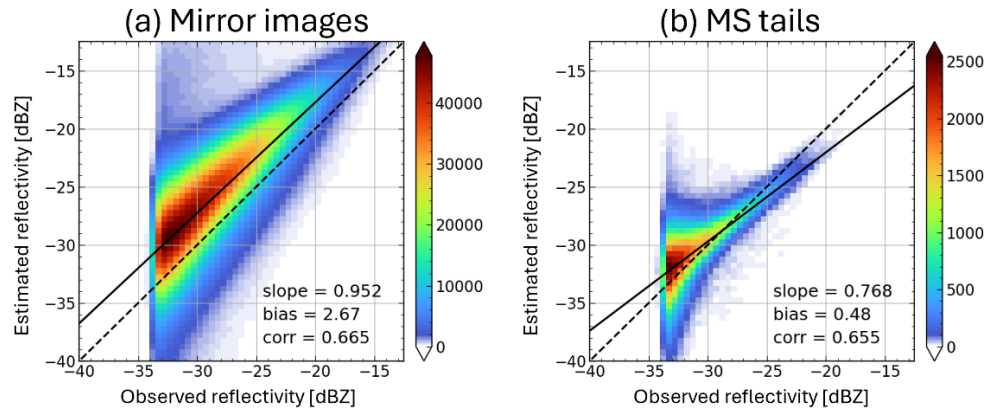


Figure 3: Joint histograms of observed and estimated radar reflectivity factor for echoes classified as certain (a) mirror images and (b) MS tails during 2025.

Similarly, we revised the MS-tail classification to use the metric ΔZ_{MStail} , as described below. Figure 3b also confirms that the estimated and observed Z values are generally comparable.

Line 234–240

Figure 2e presents an example of the estimated Z_{MStail} profile. As for the detection of mirror images, the difference between the observed and estimated Z was calculated by $\Delta Z_{\text{MStail}} \equiv Z_{\text{MStail}} - Z_{\text{obs}}$, and echoes were flagged according to whether $\Delta Z_{\text{MStail}} > g(h)$ was satisfied. When mirror images and MS tails occurred simultaneously, the larger of the estimated Z_{MI} and Z_{MStail} was used for flagging. Figure 2f shows the resulting classification and demonstrates that the false echoes aloft can be successfully identified. In some areas, the estimated Z_{MStail} extends downward to altitudes where it overlaps with genuine cloud echoes. However, because its intensity is weaker than that of the cloud echo, no flag is assigned in those regions. The histogram shown in Fig. 3b also confirms that the observed and estimated values of are in reasonable agreement.

Line 197 - what is the physical interpretation of the height h_c ?

The parameter h_c was introduced empirically to fit the observations and does not necessarily have a specific physical interpretation. We have added the following clarification to the revised manuscript.

Line 230

Note that h_c is introduced empirically to limit the slope and does not necessarily have a unique physical interpretation associated with radar signals or microphysics.

Line 216 - Can the typical echo power be replicated by a model that included the path attenuation, ocean reflection coefficient, and satellite radar cross section? Also, please elaborate on the idea of H_{SMI} being independent of PRF. In the case $H_{\text{sfc}}=0$, $H_{\text{SMI}} = -H_{\text{sat}} \bmod R_u$. This is independent of PRF because PRF depends on H_{sat} ? This would suggest that PRF depends on $1/H_{\text{sat}}$... In short please clarify the SMI at 2.4 km, independent of PRF.

Thank you for pointing this out. Regarding the estimation of SMI echo power can be formulated, a reliable quantitative estimate remains difficult. Please see our response to the comment on Line 75.

Also, thank you for pointing out that our discussion of the apparent independence of PRF was insufficient. We have added the following detailed explanation, together with the new Figs. 5 and 6:

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.

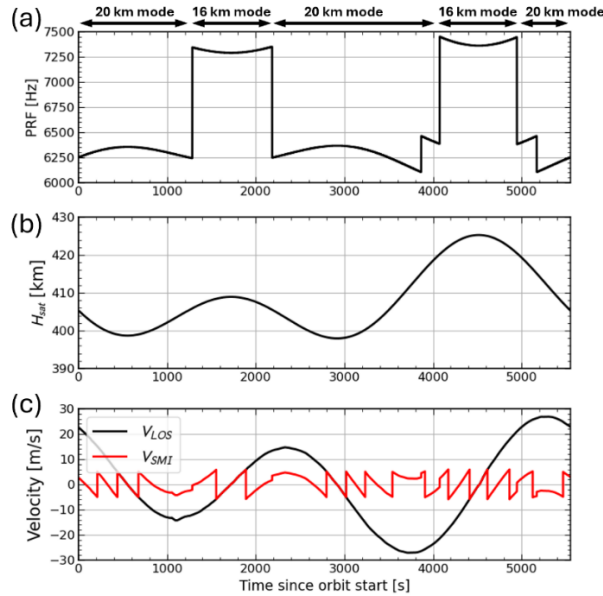


Figure 5: (a) PRF; (b) H_{sat} ; and (c) V_{LOS} and expected V_{SMI} calculated assuming $V_{sfc} = 0$ during one orbit of orbit number 06198 on 1 July 2025.

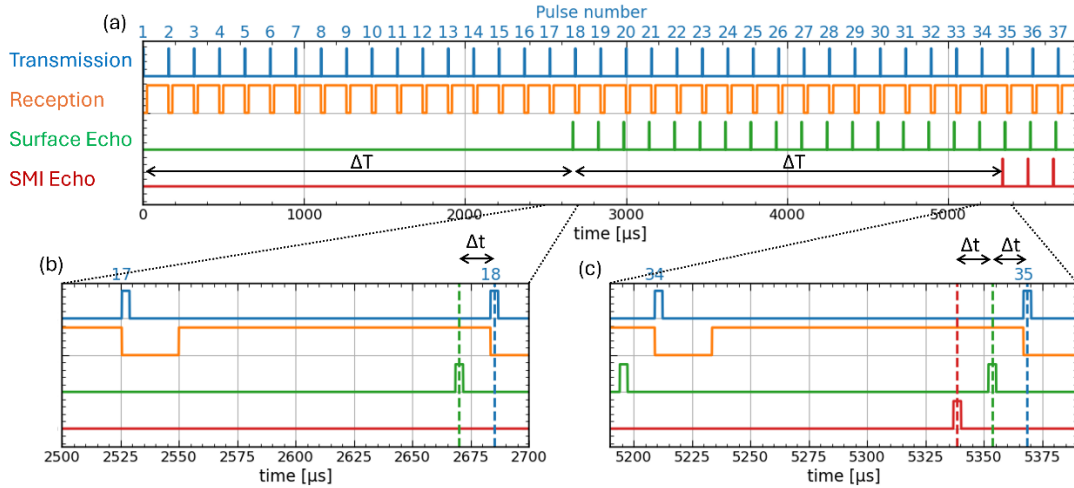


Figure 6: Timing diagrams of the radar transmission and reception windows, together with the received pulses from the surface and the SMI, for an example in the 20 km mode at a satellite altitude of approximately 400 km.

Line 225 - what is $V(H_{sfc})$? - actual surface motion, as in ocean?

The Doppler velocity provided in the CPR products is derived from the measured pulse-pair covariance and corrected for contamination by the satellite velocity in the line-of-sight direction, V_{LOS} . If this correction were perfect, the retrieved velocity at the surface would be zero. In practice, however, small residual velocities on the order of 0.1 m s⁻¹ remain because of uncertainties in and variations in surface scattering characteristics. We therefore explicitly use the observed rather than assuming it to be zero. We recognized that a more detailed explanation of these Doppler velocities is important for interpreting our results. We have therefore added the following explanation to the revised manuscript:

Line 315–318

Ideally, $V(H_{sfc})$ would be zero after V_{LOS} -correction. In practice, however, small residual velocities on the order of 0.1 m s⁻¹ remain because of uncertainties in V_{LOS} and variations in surface scattering properties, including effects associated with nonuniform beam filling (NUBF) and the strong incidence-angle dependence of specular reflection. We therefore use the observed $V(H_{sfc})$ explicitly rather than assuming it to be zero.

Line 295 – should the ending phrase be “regardless of whether CTH_ATL are evident or not” ? Or maybe an alternative is “independent of the value of CTH_ATL”.

Line 309 – Figure 9 is referenced prior to Figure 8. It looks like a typo and should be Fig 7b.

Thank you for pointing these out. We revised the manuscript accordingly.

Line 333 and Figure 8 a and b – why do the MI clouds appear to come down to a lower level in the 18 km mode than in the 16-km mode?

The more frequent extension of second-trip echoes to lower altitudes in the 18 km mode than in the 16 km mode in Fig. 12 (previous Fig. 8) arises from differences in the latitude ranges over which the two modes are operated (Imura et al., 2026). The 18 km mode is used at lower latitudes and therefore includes observations of tropical clouds with high cloud tops, whose second-trip echoes can extend to lower altitudes. In contrast, the 16 km mode is used at higher latitudes, where the observed clouds generally have lower cloud tops. We have added an explanation of this point to the revised manuscript as follows:

Line 416–420

The apparent tendency for second-trip echoes to extend more frequently into the lower troposphere in the 18 km mode (Fig. 12b) than in the 16 km mode (Fig. 12a) is primarily attributable to the different latitude bands in which the two modes are operated (Imura et al., 2026). The 18-km mode is used at lower latitudes and therefore includes observations of tropical deep clouds, allowing second-trip echoes to appear at lower apparent altitudes. In contrast, the 16-km mode is operated only at higher latitudes, where cloud tops are generally lower and the corresponding second-trip echoes remain at higher altitudes.

Line 354 and Figure 9 – I'm not clear on why the fraction color bars go either to 1 or 0.25. Please clarify.

Because multiple-trip echoes occur less frequently than the features shown in the other panels, we initially used different color-bar ranges to improve their visibility. However, this could give the misleading impression that these echoes occur more frequently than they actually do. We have therefore revised Fig. 13 (previous Fig. 9) to use the same color-bar range for all panels.

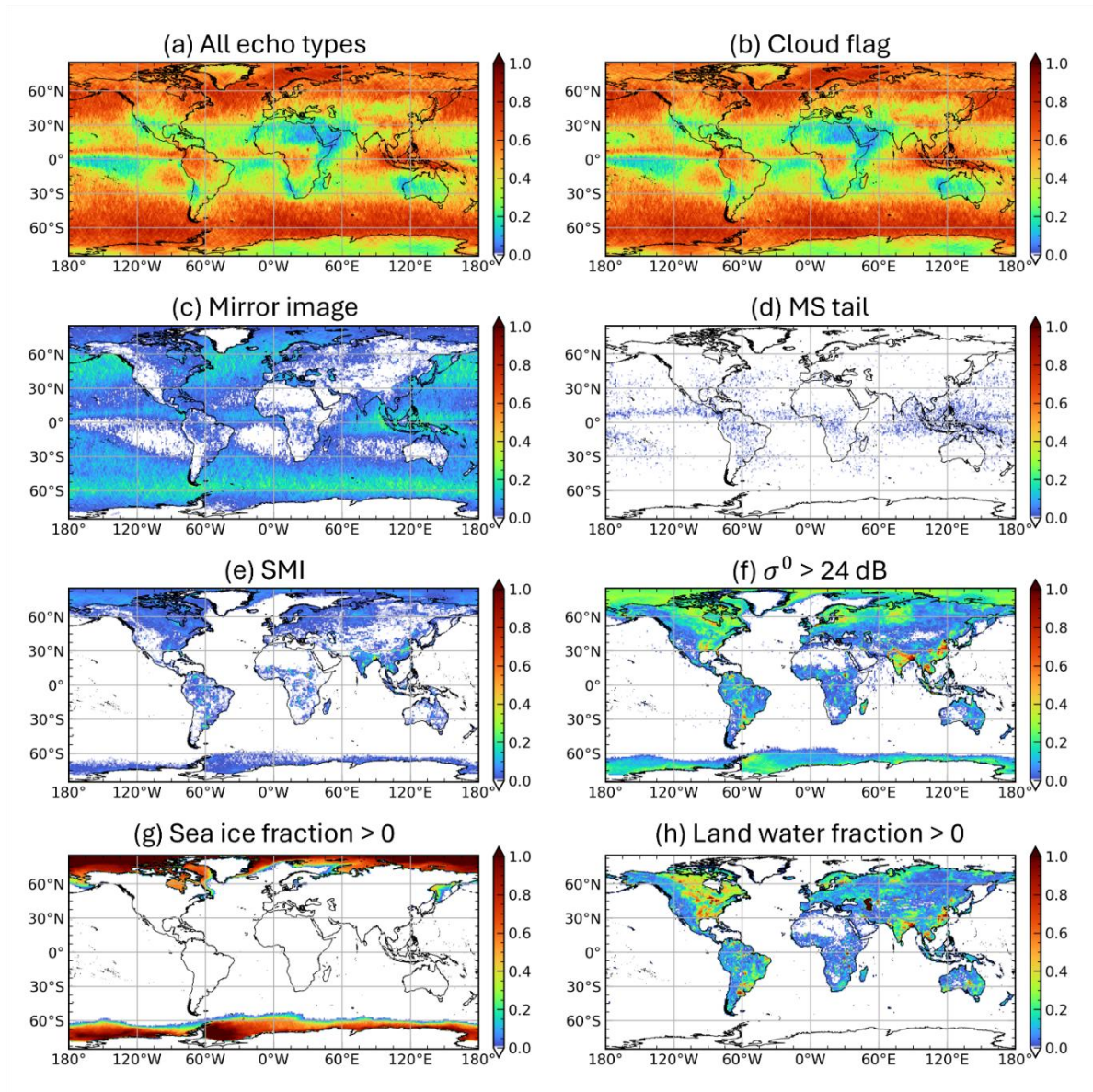


Figure 13: Maps of annual-mean occurrence frequency for each echo category: (a) all echo types, (b) clouds, (c) mirror images, (d) MS tails, and (e) SMIs, as well as the frequency of (f) strong CPR surface backscatter with $\sigma^0 > 24$ dB, (g) sea-ice occurrence, and (h) inland-water occurrence.

Line 422 – The sentence starting with “As implied ...” is not clear to me. It seems that MI does not occur either with low σ^0 (surface reflectivity) or high attenuation, but I’m not clear on how that relates to the occurrence frequency of cloud echoes in Fig. 11b.

Thank you for pointing this out. Cloud occurrence at low σ^0 itself is not directly related to mirror-image occurrence. Rather, we intended to explain that hydrometeors within clouds can produce substantial attenuation along the four-way path between the target and the surface, corresponding to the third term in Eq. (3), and thereby suppress the mirror-image signal. We have revised the manuscript as follows to clarify this point.

Line 516–518

In contrast, the occurrence frequency is low at low σ^0 values (< -10 dB). This is likely because the transmitted radar pulse is strongly attenuated by hydrometeors along the four-way path between the target and the surface (the third term in Eq. (3)), such that little energy remains to be reflected back to the CPR antenna.

Line 453 – the lowest possible MI altitude – this is computed for each Z profile in Figure 8 using CTH_{ATL} .
Is that true here as well?

Thank you for this question. Yes, this additional criterion based on is applied separately to each profile using the same procedure as in Fig. 12 (previous Fig. 8). We have clarified this point in the revised manuscript.

Line 546–549

Cloud echoes were defined as echoes that were not classified as any type of multiple-trip echo. In addition, to exclude residual second-trip echoes that may have been missed by the flag, suspected echoes more than 500 m above CTH_{ATL} and above the lowest possible mirror-image altitude were excluded. The lowest possible mirror-image altitude was calculated for each observed profile in the same manner as the red line in Fig. 12.