Response to Referees and Reviewers

September 30, 2025

Manuscript egusphere-2025-3573 "The Estimation of Path Integrated Attenuation for the EarthCARE Cloud Profiling Radar"

1 Referee Comments (RC1)-Matthew Lebsock:

1. Line 42: Add Lebsock and Suzuki 2016 DOI:10.1175/JTECH-D-16-0023.1.

   Thank you for pointing this out. Added the reference in the revised manuscript.

2. Equation 6: I agree that the fact that there are differences in the equation is an advantage IF the water vapor profile and the surface wind speed are approximately equal at points x and x_1. However, in the presence of cloud at point x and clear sky 'calibration point' at x_1 we don't expect this to necessarily be true, especially for small scale unresolved by the model fields from which water vapor is derived. For example, Lebsock and Suzuki 2016 show using an LES that water vapor attenuation is larger in the cloudy targets than the clear targets, which makes physical sense.

   Thank you for your comment. We understand that Equation 6 relies on modeled water vapor and surface conditions, so its accuracy depends on how well the model represents these fields at both points. Small-scale differences, such as higher water vapor over clouds compared to clear-sky points, may lead to slight underestimation of hydro attenuation. This limitation is common to any PIA retrieval method, because the gas attenuation has to be computed anyhow (which needs an assumption on water vapour profiles).

3. Line 112: 'chose' → 'chosen'.

   Corrected in revised manuscript, Thank you.

4. Figure 1: I need help with this figure. First, I think you should show another panel with both the 'model-method' and 'interpolation-method' error plotted as a function of wind speed. Second, I think you should label on the existing panel which region is best for each method for clarity. Third, I can't quite understand why the interpolation method is better for a much greater distance between x and x_1 when the wind speed at x_1 drops below about 3 m/s. I actually would expect the opposite – that the interpolation would work better over greater distances for higher wind speeds . Fourth, the residuals should be a function of both the wind speed at x and the wind speed at x_1 since they each influence one of the σ_{0e} terms. Can you comment on points 3 and 4?

   Thank you for this suggestion.In response, we conducted additional analysis to better characterize PIA uncertainty.

   Regarding the influence of calibration-point wind speed, we agree that in principle the residuals depend on both the wind speed at the cloudy profile (x) and at the calibration point (x_1), since each influences one of the σ_{0e} terms. o capture this, we segregated residuals by wind speed at x and x_1 and constructed two separate PIA uncertainty lookup tables (LUTs):

   - Using calibration points for which $|\mathrm{Wind}(x) - \mathrm{Wind}(x_1)| \leq 2$ m/s (Fig. 1).
   - Using calibration points for which 2 m/s $< |\mathrm{Wind}(x) - \mathrm{Wind}(x_1)| \leq 4$ m/s (Fig. 2).

   The regions in the LUT plots where each method performs best are labeled.

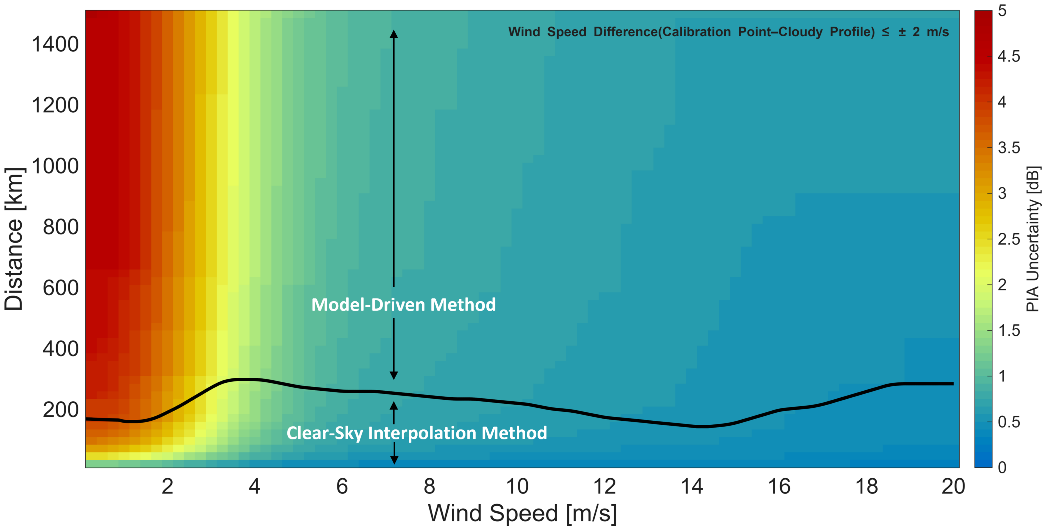

Figure 1: Lookup table of PIA uncertainty based on calibration points absolute wind speed difference within 2 m/s from the cloudy profile. The x-axis shows the wind speed of the cloudy profile, and the y-axis indicates the distance to the calibration point. The black line marks the boundary beyond which the model-driven method is preferred.

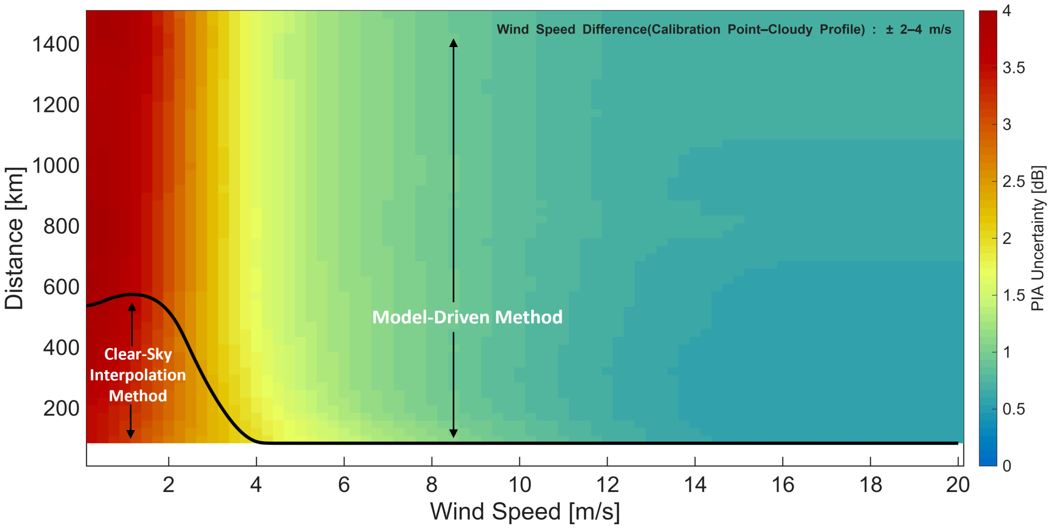

Figure 2: Lookup table of PIA uncertainty based on calibration points with an absolute wind speed difference greater than 2 m/s but no more than 4 m/s from the cloudy profile. The x-axis shows the wind speed of the cloudy profile, and the y-axis indicates the distance to the calibration point. The black line marks the boundary beyond which the model-driven method is preferred.

Within ∼85 km of the cloudy profile, winds are generally correlated, and most calibration points fall within ±2 m/s limits.

To address point 1, we are including two panels comparing PIA uncertainty from the model-driven and interpolation methods as a function of the cloudy profile wind speed:

- Using calibration points for which $|\mathrm{Wind}(x) - \mathrm{Wind}(x_1)| \leq 2$ m/s, for varying distances. (Fig. 3).
- Using calibration points for which 2 m/s $< |\mathrm{Wind}(x) - \mathrm{Wind}(x_1)| \leq 4$ m/s, for varying distances. (Fig. 4).

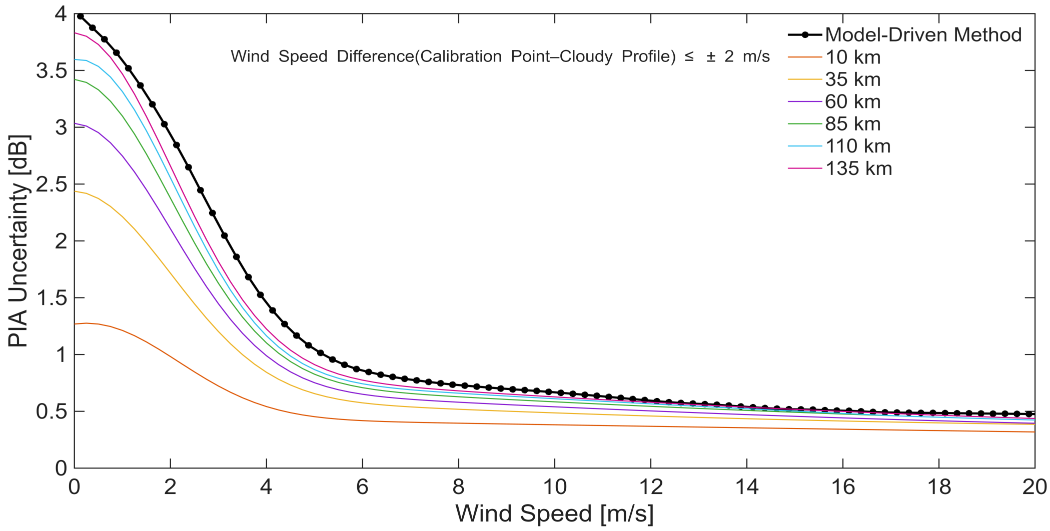

Figure 3: PIA uncertainty from the model and clear-sky interpolation using calibration points with an absolute wind speed difference within 2 m/s from the cloudy profile, for varying calibration point distances. X-axis: wind speed of the cloudy profile; Y-axis: PIA uncertainty.

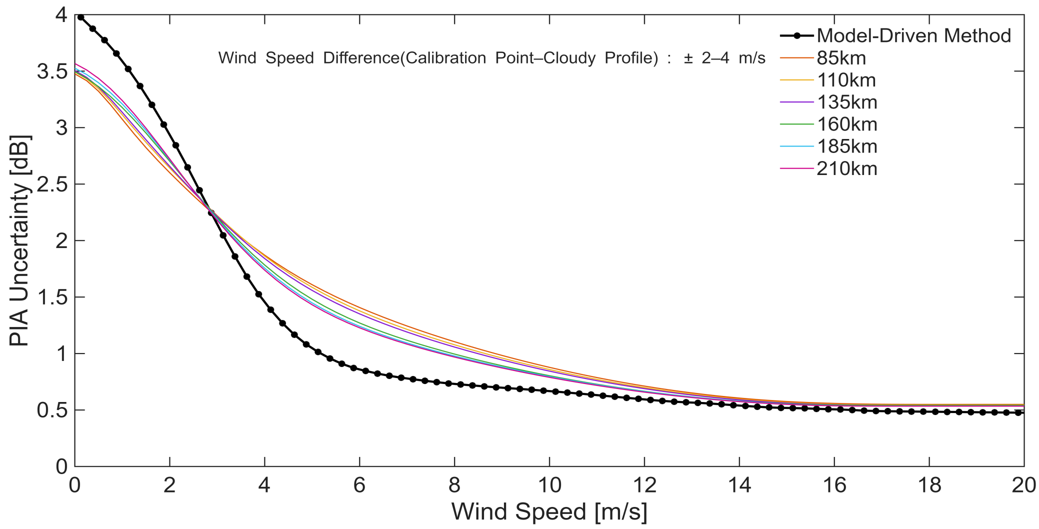

Figure 4: PIA uncertainty from the model and clear-sky interpolation using calibration points with an absolute wind speed difference greater than 2 m/s but no more than 4 m/s from cloudy profile, for varying calibration point distances. X-axis: wind speed of the cloudy profile; Y-axis: PIA uncertainty.

According to Fig.3, when calibration points within ±2 m/s are used, interpolation with clear-sky profiles generally yields lower uncertainty, particularly within 50 km, and the advantage is most pronounced at low wind speeds (<4 m/s). As distance increases, interpolation's advantage diminishes, and uncertainty converges to the model-driven method.

According to Fig.4, using calibration points with an absolute wind speed difference of 2-4 m/s from the cloudy profile, interpolation generally performs worse than the model, except at very low winds (<2.5 m/s), where it shows lower uncertainty than both the ±2 m/s case and the model. In all other cases, the model-driven method is preferred.

Comparison with the previous PIA uncertainty LUT, which included all calibration points, shows the following:

- Using only calibration points within ±2 m/s allows interpolation over larger distances at high wind speeds (>5 m/s) compared to the previous LUT (150–250 km vs 100–200 km), due to stronger wind correlations.

- At low wind speeds, uncertainty is higher, and the previously observed feature, interpolation over thousands of kilometers, is no longer present. This arises from calibration-point selection: using points with absolute wind speed difference more than ±2 m/s relative to the cloudy profile generally produces lower uncertainty at larger distances in low-wind regimes. The previous LUT included all calibration points, effectively incorporating this feature and allowing interpolation over greater distances. Generally, as distance to calibration point increases, at low wind speed regimes, the uncertainties of both the interpolation and model-driven approaches are similar, typically in the 3-4 dB which reflects the fact that both approaches perform similarly poorly under such conditions.

Finally, although residuals depend on both the wind speed of the cloudy profile and the calibration point, our analysis shows that PIA uncertainty is mainly controlled by the distance to the calibration point. At short distances, winds are more similar, reducing uncertainty, while at larger distances, divergence increases. Most data within the allowed interpolation range fall within ±2 m/s of the cloudy profile wind speed, so distance remains the dominant factor, as reflected in the previous PIA uncertainty look-up table.

5. Line 159: Related to point above about low wind speeds here you say you exclude the low wind speeds from interpolation which is what I would expect. 'In contrast, the method used here allows interpolation even when the calibration points are 200 km to 100 km from the cloudy pixel in wind speed conditions between 4 and 15 m/s'.

   In practice, interpolation is not applied at very large calibration distances in low wind speed regimes, since in these conditions the uncertainty from both methods is already similar. Extending interpolation to such large distances can actually degrade the performance.

6. Line 164: I think you will get an even better uncertainty estimate if you bin by wind speed at both x and x1. 'Each calibration point used in the PIA estimation is weighted based not only on it's distance from the point of interest 165 but also on the potential uncertainty associated with wind speed at that location'.

   We agree that both wind speeds (at x and x_1) can influence the uncertainty. However, our analysis showed very similar behavior when segregating by both variables, with distance to the calibration point remaining the dominant factor, as already summarized in the figure.

7. Equation 14: Several terms are not defined: lambda, c, tau_p.

   Thank you for the comment. We have defined all previously undefined terms in Equation 14.

8. Lines 288-300: The 'model' used in precip-column is actually an empirical look-up-table derived from clear sky observations not the li model. 'The first approach, referred to as the Wind/SST method, estimates the NRCS at cloudy region in absence of hydrometeor and presence of gaseous attenuation (σ gas 0) as a function of surface wind speed and SST using geophysical models (Li et al., 2005)'.

   We acknowledge this correction. The initial description followed the 2C-PRECIP-COLUMN documentation, but in the revised manuscript we will clarify that the approach relies on an empirical look-up table derived from clear-sky observations, and not directly on the Li et al. (2005) geophysical model.