# Response to reviewer 2 comments

The author responses are in blue

**General Assessment**

This paper makes an important contribution to EarthCARE and the achievement of quality Doppler measurements from space. The methodology for addressing satellite pointing accuracy is generally sound, however I have identified several concerns regarding the fundamental assumptions about surface Doppler velocity measurements that should be addressed before publication.

**Major Concerns**

My primary concern stems from the statement on Page 5 Lines 118 that "Therefore any departure from the expected 0 m/s velocity indicates a potential mispointing." I guess this is somewhat true, but the quantitative level of departure will depend not only on the pointing angle of the antenna but also the NRCS of the surface at different angles. The surface backscatter will vary statistically with angle, and this will have the effect of causing non-zero-mean NUBF.

We thank the reviewer for this insightful comment. We agree that surface Doppler velocities can be affected by non-uniform beam filling (NUBF) effects, including those arising from variations in surface backscatter with incidence angle. However, we would like to emphasize that NUBF-induced biases in Doppler velocity are minimal for small angular deviations over spatially homogeneous surfaces (Tanelli et al., 2002). In our case, the NRCS variability within the angular pointing range considered (approximately ±0.01º) is very small. As a result, the NUBF-induced biases over the regions used for the mispointing assessment are negligible at this level of precision.

As noted in the manuscript (line 172), we do apply a correction for NUBF. However, we acknowledge that this correction should be introduced earlier in the text. We have therefore revised the sentence in line 118 to read:

*Therefore, any departure from the expected 0 m/s velocity, after correcting any potential NUBF effects, indicates a potential antenna mispointing.*

There is significant discussion of Figure 3, but very little discussion of Figure 3-a. Figure 3-a appears to show that while the mean surface Doppler velocity of the oceans are consistent with latitude, the Doppler velocity of the land surface varies significantly. This does not appear to be a noise issue, as the standard deviation in Figure 3-b does not show the same features as Figure 3-a. This matches my expectation above.

Having the surface Doppler technique potentially not0 work as well over land does not surprise me, but I'm concerned that if the remainder of this work includes the land surface Doppler velocity, it will cause added uncertainty on the order of 0.5 m/s (a visual estimate of per-latitude mean Doppler changes between land and ocean at the same latitude).

The current text discusses variability (around Line 160) and states that flat surfaces are expected to introduce no vertical motion at nadir. I do not agree with this statement due to how NRCS changes with angle. Further, the data in Figure 3-a do not appear to show a lack of flat-terrain-induced apparent vertical motion. Certain areas of flat land (such as the Great Plains in North America) show significant mean difference from the ocean data, while the Rocky Mountains to their west match the mean ocean velocity.

We thank the reviewer for the observation regarding the differences between land and ocean Doppler velocities in Figure 3a, and the implication that land surface Doppler measurements may introduce additional uncertainties.

Indeed, NUBF effects over land are significantly more pronounced, and there is no well-established methodology for correcting them. The interaction between the radar footprint and the surface, including variable slopes and heterogeneous scattering, introduces uncertainties that are difficult to characterize. Not only orography but surface types also play a key role, affecting both the mean and variability of the Doppler velocity measurements. These effects are often correlated with along-track NRCS gradients. In some regions, the NRCS variability can be up to 30 times higher than that observed over the ocean. For these reasons, land surface Doppler velocity measurements are excluded from the antenna mispointing analysis.

An exception to this is snow-covered land, particularly Antarctica and Greenland. These surfaces are relatively uniform, exhibit low Doppler velocity bias and variability, and are located at latitudes where the CPR operates at high PRF. This leads to improved measurement precision and makes these regions valuable for our antenna mispointing study.

We acknowledge that the description of Figure 3a, the variability discussion and the introduction in section 4 can be expanded for clarity. The revised text now reads:

*While the results highlighted in Figure 3 do not differentiate between ascending and descending orbits, panel (a) already reveals a clear latitudinal structure in surface Doppler velocity over the oceans, suggesting potential mispointing, especially in the northern hemisphere (darker colors). In contrast, land surfaces exhibit considerable spatial variability and regional biases that deviate from the oceanic trend. These biases are not uniformly correlated with orography but are also linked to the heterogenic characteristics of the surface.*

*[…]*

*One of the most notable characteristics of the surface Doppler measurements is their variability, which is dependent to orography, surface type and the CPR PRF settings. The lowest Earth's surface Doppler velocity variability is observed over ocean and snow-covered land (e.g., Antarctica and Greenland). Flat and uniform surfaces are expected to introduce no vertical motion at nadir, whereas heterogenic and rough topography can generate heterogeneous scattering and significant terrain-induced Doppler effects due to slopes and variations in reflectivity causing non-uniform beam filling effects (Manconi et al., 2024).*

*Consequently, land regions tend to exhibit noisier measurements, with exceptions such as the deserts of Western Australia, the Sahara, and Namibia, which have relatively uniform and flat surfaces. Sea ice, on the other hand, appears to considerably increase the measurement variability. Additionally, the high PRF settings, configured to find balance between the unambiguous range and the tropopause height (a proxy for maximum cloud top height) at different latitudes, significantly reduce the measurement variability at high latitudes (e.g., near the North Pole and Antarctica) where the PRF is at its high, further highlighting the influence of the instrument configuration on data quality.*

*[…]*

*The clear-sky Doppler velocity measurements over the ocean (free of ice) and snow-covered land (Antarctica and Greenland) collected for all orbits from June 2024 to February 2025 are used to document the biases observed in the global climatological analysis and, in order to identify any potential antenna mispointing. Other land regions are excluded from the analysis because the high variability of their surface Doppler measurements compromises the precision required for mispointing detection and the integrity of the global assessment.*

The rest of the paper is quite good, but because all the remaining data are effectively zonally averaged, this question of land-vs-ocean remains as a constant source of uncertainty, particularly in the Northern hemisphere.

We would like to clarify that only clear-sky Doppler velocity measurements over the ocean (free of ice) and snow-covered land (Antarctica and Greenland) are used to document the biases observed in the global climatological analysis and to identify potential antenna mispointing (see line 170).

On page 11 Line 255 the paper discusses a technique to ingest 250 km along-track averaged surface Doppler velocity observations. This seems like a good approach (over ocean) but there are no data shown about how this works. The statement around Line 265 that the 90th percentile of residuals remain below 0.00077 degrees is very promising, but is there some data that shows this? I don't see how it can work with the average surface velocity over land varying by ~0.5 m/s as compared to ocean.

We thank the reviewer for highlighting these points. As described in the text, the 250 km window (i.e. about 32 s integration time) is chosen as an optimal balance: it is long enough to smooth out small-scale variability, such as noise, while still preserving meaningful large-scale trends in the Doppler measurements.

Reducing the standard error by a factor of two would require acquiring four times as many observations in the sample, resulting in a window of over two minutes, already too long to capture meaningful mispointing variations at the level of precision targeted in this study.

The data shown in Figure 3 were generated using this 250 km averaging, and the results in Section 4 are both smooth and sufficiently resolved, suggesting that the selected window length is a good choice.

The results referenced in line 265 are based exclusively on surface Doppler velocity measurements over ocean and snow-covered land, using the 250 km along-track averages after correcting for NUBF effects. The 0.00077º value reflects the 90th percentile of residuals between the modeled mispointing trend and the ingested (along-track averaged and NUBF-corrected) values used in the analysis. As previously explained, land measurements (aside from Antarctica and Greenland) are not used in this assessment due to their higher variability and reduced reliability. Therefore, the ~0.5 m/s land-ocean differences do not affect this result.

**Recommendations**

Please address how variations in mean surface Doppler velocity, particularly over land, impact the overall analyses. I recommend performing these same analyses with an ocean-surface mask to determine how land-ocean discrepancies affect the results.

The surface Doppler velocity measurements over land (except for snow-covered regions such as Antarctica and Greenland) are explicitly excluded from the antenna mispointing analysis (line 170). The methodology described in the manuscript is structured to first present the global characteristics of surface Doppler measurements, followed by a careful selection of regions appropriate for a reliable mispointing estimation.

As described in the text, land surfaces are known to introduce additional uncertainties due to NUBF effects and spatial heterogeneity in backscatter and are therefore intentionally omitted from the derivation of the mispointing model.

Introduce land surface Doppler velocity measurements in the mispointing analysis would introduce substantial uncertainties and contaminate the results. Including land data simply to demonstrate that it degrades the results to later apply an ocean-surface mask would obscure the methodology rather than strengthen it.

Please provide a more detailed physical explanation for the observed land-surface Doppler velocity variations.

This has been addressed in previous responses.

**Minor Comments**

Figure 7 - The interpretation of this plot is unclear. It appears to show residual mispointing after removing seasonal effects, but the units are not specified. Please clarify what is being represented.

The figure represents the normalized mispointing trend after removing the seasonal variations. As noted, the mispointing angle is normalized, which is why no physical units are shown. We believe that the current figure caption and corresponding description in the text accurately explain what is being presented. However, if specific elements remain unclear, we would appreciate further guidance from the reviewer on which aspects require clarification.

Line 80 and Figure 1 - Please explain how cross-track geolocation is accomplished with a single overpass using terrain. If this is one overpass it could be informative to show the range-to-surface vs track distance plot combined with the terrain.

Lines 67 to 80 explain how the terrain technique works:

*For significant elevation gradients, the assessment is performed by comparing the instrument's surface detection height to a reference digital elevation model. Artificial mispointing errors are introduced in the along- and cross-track directions, and the absolute geolocation is determined by the shift that maximizes the correlation between the instrument and the DEM-estimated surface height.*

A similar example to what the reviewer suggests, showing range-to-surface versus track distance over terrain is provided in Puigdomènech Treserras and Kollias 2024, Figure 7. Since the focus of the current study is on antenna pointing rather than geolocation, we believe including such a figure here is not essential.

Figure 2 - This figure is challenging to interpret. I recommend:

- Separating the plot into two (ascending and descending) to clarify the different clustering patterns
- Making the stars indicating the mean values more prominent, and
- Replacing the yellow text with a color that provides better contrast.

We thank the reviewer for the helpful suggestions regarding Figure 2. We agree that separating the ascending and descending orbits improves the clarity of the clustering patterns, and we have now split the figure accordingly. In addition, the markers indicating the mean values have been made more prominent, and the coloured texts have been replaced. We believe these changes significantly enhance the figure's interpretability.

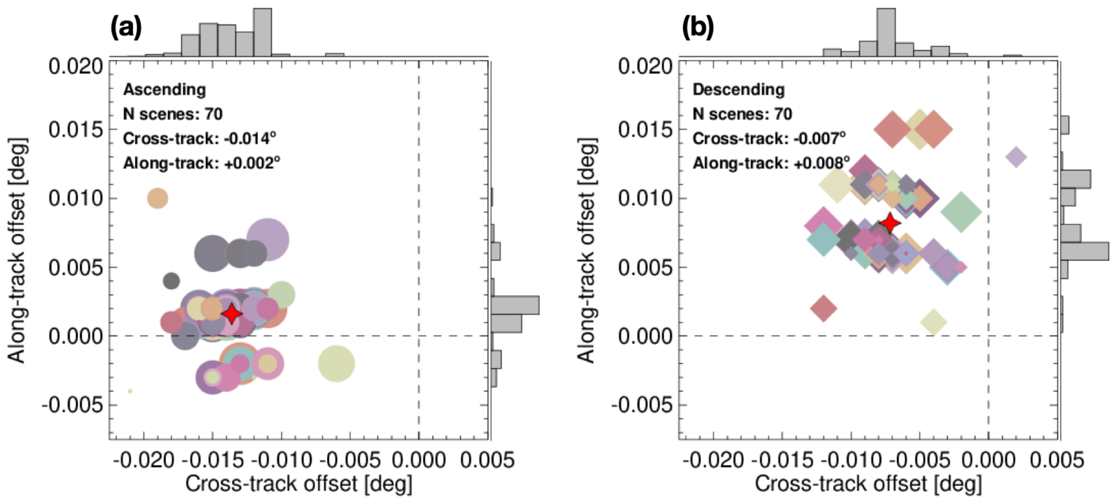


Figure 2: Combined global geolocation statistics of the EarthCARE CPR for data collected from August to November 2024: (a) ascending and (b) descending parts of the orbit. Each symbol represents an individual domain where the geolocation is assessed, with the symbol size being indicative of the number of overpasses. Distinctive colors identify different domains, while filled red stars denote the averages. The dashed lines denote the perfect geolocation point (0º).

Conclusion

While the paper represents an important contribution to the field, addressing these concerns - particularly regarding surface Doppler velocity assumptions and land-ocean discrepancies - would significantly strengthen the work.