Reply to Anonymous Referee #1

We thank the anonymous referee for his review and his detailed comments.

Below, the referee's comments can be found in bold, followed by the authors' replies.

This manuscript describes development of a clutter simulator that was applied to the WIVERN mission to generate simulated reflectivity and Doppler velocity profiles over a mountainous region in the northwest of Italy. The manuscript presents detailed analysis of a particular profile that demonstrates non-uniform beam filling (NUBF) and also statistical analysis of a collection of scans over the region. The statistical results begin to quantify the intuitive idea that regions with greater variability in terrain elevation and NRCS will generate clutter profiles with greater variability in reflectivity and Doppler.

The authors state the aim of the work is to "extend the simulations of the clutter signal to non-planer surfaces, … including a realistic variability of the surface backscatter" (lines 48-49). Their claimed novelty is "the application to a space-based configuration, the extension to the Doppler signal, and the inclusion of NUBF effects" (lines 51-54). The simulated data presented and analyzed appears to be high quality and analysis clearly illustrates NUBF and increased variability in reflectivity and Doppler profiles. The simulator considers only clutter (no atmosphere/hydrometeors simulated) and assumes no attenuation.

The work described in this manuscript is an incremental evolution of existing simulation techniques and the novelty is in the combination of high-resolution DEM with the WIVERN (W-band) mission. Other simulations with high-resolution DEMs have been previously described in the literature. The authors make no attempt to explain how the simulations would be useful for the WIVERN mission other than vague statements about how it may be difficult to use Doppler velocity as an antenna characterization technique over rough terrain (lines 10-11; 35-46; 223-225).

Better understanding the shape of the clutter reflectivity and of the clutter mean Doppler velocity profiles is important for two reasons: 1) the reflectivity profile can be used for geolocation purposes and its shape is relevant for assessing the blind zone of a radar system (i.e. the region where the radar signal will not provide any useful information for the hydrometeors); 2) the surface Doppler can be used in a data-driven approach to mitigate mispointing errors associated to thermoelastic antenna distortions. This last aspect is being demonstrated by the EarthCARE CPR, currently in commissioning phase, which is using the ocean surface return as a reference for a data-driven mispointing calibration for distortions that vary along the orbit because of the changing sun illumination. The calibration of distortions that occur on shorter time scales needs more frequent calibration points. Therefore, it must be assessed what surfaces can be useful for this kind of purpose. The limits of acceptable variability in terms of sigma-zero and orography have to be addressed.

There is no attempt to quantitatively link the simulated clutter Doppler profiles to potential errors in mispointing corrections or any other aspects of the mission. For these reasons it is difficult to see how the manuscript meets the criteria of scientific significance required by this journal.

The errors in Doppler velocity measured at the surface at boresight can be converted to mispointing angle error (Scarsi et al., 2024). The mission requirements for the horizontal component of the line-of-sight wind measurements is in the order of 2.5 m/s: to achieve this goal, the contribution on mispointing errors must be lower than 0.4 m/s after all possible calibration methods (ESA-WIVERN-Team, 2023). The on-board attitude determination and control system can provide pointing of the antenna with an uncertainty of the order of 1 m/s, thus not sufficient to meet the science requirements of the mission. In addition, thermoelastic deformation of the antenna is another large contribution to the pointing error, as confirmed during the commissioning phase of EarthCARE. This effect is cyclical with the orbital period and it's very hard to model and predict numerically, even using temperature sensors attached to the antenna. However, it produces a large effect on the mispointing of the boresight, even in the order of 1 m/s. For the WIVERN antenna thermoelastic deformations are expected to have the same magnitude (ESA, industrial studies). This effect must be corrected with additional methods, e.g. by looking into the surface Doppler velocity: calibration methods need natural targets, and the surface is the simplest one available.

Introduction and conclusions section have been reworked in the revised manuscript to better illustrate these points.

I suggest the authors make major revisions to this manuscript to address the issue of scientific significance before the manuscript is accepted for publication. In particular, the authors should make clear why it is a "substantial contribution" beyond existing simulation methods and make clear what benefits it will contribute to the WIVERN mission.

To our knowledge, there is no clutter simulator of reflectivity and Doppler signal for spaceborne radars taking into account NUBF for ground return and orography that has been developed for the GPM, CloudSat, EarthCARE, or INCUS missions. So, we think this is a first. Of course it is more relevant for the WIVERN mission which has Doppler capabilities and is conically scanning.

This clutter simulator is a module of a larger end-to-end simulator endeavour being developed as part of the phase A activity funded by ESA, which simulates the full return from both atmospheric and surface targets, based on the simulator already developed at Politecnico di Torino (*Battaglia, A., Martire, P., Caubet, E., Phalippou, L., Stesina, F., Kollias, P., and Illingworth, A.: Observation error analysis for the WInd VElocity Radar Nephoscope W-band Doppler conically scanning spaceborne radar via end-to-end simulations, Atmos. Meas. Tech, 15, 3011–3030, 2022*; Rizik et al., 2023; Battaglia et al., 2024). This work completes the simulator adding a thorough treatment of the surface accounting for variability of sigma-zero at fine scales and orographic effects. In the previous simulator, the surface was treated in a simplistic way (flat and homogeneous) which is sufficient for oceanic surfaces. It is interesting, however, to understand land surface return to assess the surface Doppler for calibration and the relative strength of the signal from the clutter and from the atmosphere. Ongoing studies and private communications with the EarthCARE team (Pavlos Kollias and Bernat Puigdomènech Treserras) have highlighted the importance of such aspects.

Following these comments, revisions to the introduction and conclusion sections have been made to better illustrate the scope of our work.

The following are other suggested corrections:

Lines 33-34: Introduction states "It is therefore timely to investigate and assess how beneficial such a scanning configuration could be in terms of reducing the signal-to-clutter ratio." This topic is not addressed again in the manuscript and it is not clear how the simulator in its current state would contribute to such an investigation without simulating the atmosphere. Please clarify how the clutter simulator addresses this issue. Specifically how can the simulator be used in its current state when attenuation and scattering above the surface are neglected.

The simulator is intended as a module of a larger end-to-end simulator which aims at simulating the radar observations using results from numerical weather prediction models, expanding on the currently simple implementation of the ground clutter signal. The simulator of course accounts for attenuation and scattering in the atmosphere. For the surface clutter the only impact from the atmosphere will come from attenuation and thus to a reduction of the clutter SNR (which is usually high).

Revisions in the introduction and conclusions sections made regarding the previous comments also address this issue.

Line 60: NRCS model is an input that should be included in the description

Figure 2 has been updated following this recommendation. The “NRCS model LUTs” block has been added to the inputs.

Eqns 1, 4, 6 are stated as functions of r (LHS) but written as functions of t (RHS), please make them consistent.

The issue has been fixed by substituting $2r/c$ in Eq. 1 with $2\xi/c$ (where ξ is the distance between the infinitesimal element dS and the radar, this remark has been added in line 79), then t has been changed to $2r/c$ in Eq. 1, 4 and 6.

Line 85: Indicate what limitations the statement “No attenuation effect has been included” places on the utility of the simulator.

Attenuation is easy to take into account, and it has been considered in the full simulator. The Doppler signal is not affected by attenuation as far as the SNR remains high, as is the case for surface targets. The shape of the reflectivity profile is also unchanged (atmospheric attenuation simply decreases the profile by the path integrated attenuation of the whole atmospheric column).

Line 89: Justify choice of flat (plane) integration implicit in del x_ij del y_ij formulation of infinitesimal and why that is an appropriate choice even though spherical earth assumption is used otherwise in the model.

Δx_{ij} and Δy_{ij} are the sides of the rectangular planar elementary elements (pixels) considered in the integration, and they depend on latitude and longitude. They are calculated as $\Delta x_{ij} = R_E \cos(lat)\, \delta_{lon}$ and $\Delta y_{ij} = R_E\, \delta_{lat}$, where R_E is the Earth’s radius, δ_{lat} is the DEM resolution in latitude and δ_{lon} is the DEM resolution in longitude. The 3D orientation of the pixel and the stretching that originates from the orographic variability is taken into account by the term $\cos(\beta_{ij})$, which is the slope of the pixel with respect to the local tangent plane to Earth’s sphere. Therefore, the area of the pixel changes taking into account the DEM variability in height, as the terms used to calculate β_{ij} are expressed in the ECI frame. To summarize, the surface, locally at each pixel, is approximated with inclined facets whose inclination is given by β_{ij} which is computed according to the local slope of the terrain. This approximation is deemed appropriate since the resolution of the DEM is 30 m.

A note has been added to line 89 to better illustrate this concept.

Line 139: The method proposed in Battaglia et al. (2024) is cited but that reference is currently unavailable (submitted) so this method cannot be evaluated in the context of this manuscript.

The methodology developed was already explained in *Battaglia et al., "Observation error analysis for the WInd VElocity Radar Nephoscope W-band Doppler conically scanning spaceborne radar via end-to-end simulations", Atmos. Meas. Tech, 2022*, and further improved in Battaglia et al., 2024. The paper has been accepted with minor reviews and should be out soon. A version of the paper in the accepted form can be sent to the reviewers in confidential form. The first reference has been added to the bibliography and line 139 has been updated.

Line 157-159: The choice of these two cases is important in understanding the applicability of the work. The results would be strengthened by citation or further justification for the choice of the high correlation case. This is needed to give context to the conclusion "high correlation value … produces much better results and seems very promising" (line 231-232). rho on these lines should be changed to rho_HV

The two adopted cases result from two different methods to calculate the Doppler signal return. The first originates by correlating the H and V signals from the actual surface range. Unfortunately for land surfaces the correlation between the H and V reflection signals is low (of the order of 0.5 as observed from airborne observations, Wolde et al., 2019). The second originates from correlating the surface ghosts (Rizik et al., 2023), which have a much higher correlation but lower signal-to-noise ratio (but still much larger than 0 dB) because of the large sigma-zero of land surfaces. The figure below better explains these two different methods to derive the estimates of the surface Doppler.

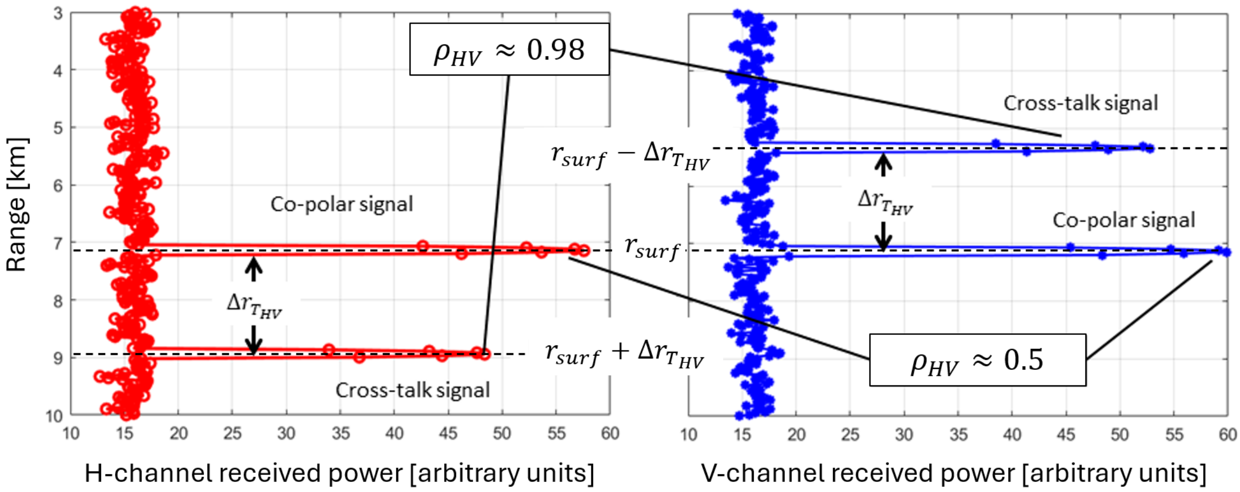

Figure 1: schematic describing the two possible methods for deriving surface Doppler based on pulse pair estimates.

In the first case co-polar signals at the same range (the surface in figure, at r_{surf}) in the H and V channels are used: this offers higher SNR compared to the other method (by 5 dB, 10 at maximum) but the correlation is lower (around 0.5) due to the scattering characteristics of land surfaces. In the other case, the two cross-talk signals are used at different ranges, in particular separated by a range equal to $2\Delta r_{T_{HV}} = 4T_{HV}\ c$, where T_{HV} is the interval between H and V pulses, 20 μs (this value was missing from Table 1, it has been added in the revised manuscript). The two co-polar signals at the surface range correspond to the H (first) and V (second) separate pulses sent T_{HV} one after the other bouncing back from the surface without changing polarization. The two cross-talk signals originate from the same H or V pulses which are backscattered in the cross polarization and therefore appearing at different ranges (higher above or below the surface). For these signals the return power is lower but the correlation is much higher because of reciprocity.

In the revised manuscript, Section 2.3 has been reworked to better address this aspect.

The mistake about the ρ_{HV} notation has been fixed in the revised version.

The case studies section should be reworked with emphasis given to readability.

The case studies section has been reworked in the revised manuscript.

Line 242: Please describe the renormalizing procedure.

The height at which the boresight intercepts the surface of the DEM (i.e. at the range of the surface along the boresight) is subtracted from each profile height.

Line 274-276: Indicate what value would be gained by improving the NRCS dataset, specifically what benefit would justify an additional field campaign. Also indicate what value the simulator would bring to the EarthCARE and CloudSat missions.

The NCRS dataset used to build the LUTs of Fig. 4 is outdated, coming from experimental campaigns carried out in the 1980s. At that time there was not much interest in higher frequency bands. Higher incidence angles are missing (the sampled incidence angles are also sparse) and for some class terrains the Ka or Ku band values had to be used due to missing data in the W band. In particular it is very important to better establish the drop in NRCS when moving from nadir to very slant angles on surfaces like different types of snow, sea ice and different land biomes.

The Doppler value from the surface can be used as a reference for calibration of mispointing of the antenna in real applications, such as the EarthCARE mission. Also better understanding the clutter impact on the hydrometeor profiling can be of interest, e.g. for orographic precipitation studies.

These observations have been added to the conclusions section following the referee's comment.