Response to reviewer's comments-

The responses are in blue text.

The authors present results of C-band radar backscatter simulations for snow covered ground, applying a bi-continuous dense medium radiative transfer model for computing scattering in the snow volume and the Numerical Solution of Maxwell's Equation in 3-D (NMM3D) method for ground surface scattering. A main motivation for the study is the proof of the hypothesis that in case of deep snow the C-band cross-polarized backscatter contributions of the snow volume exceed the cross-polarized backscatter signal of the ground surface. For tuning of model input data and validation C-band VV- and VH-polarized Sentinel-1 backscatter time series data of three high elevation sites in the French Alps are used. The topic of the paper, C-band radar wave interaction with seasonal snow, is of great relevance for advancing methods for deducing physical snow properties from satellite-borne radar data. However, the manuscript provides a rather narrow view on this topic, lacking actual observations of physical properties of the snow and ground media for model input and validation, as well as lacking specific information on properties of the Sentinel-1 data used at the different locations.

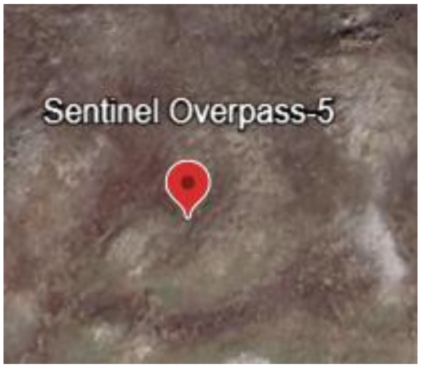
Main issues:

The model input data for describing the interaction mechanism of the radar signal with snow and ground are purely hypothetical, not based on observations of physical properties, morphology and temporal evolution of the snowpack, nor on physical properties and state of the ground in the snow-free and snow-covered cases. This kind of information is essential for testing and validating models on radar wave interaction with natural media. The authors selected sites for model testing and validation where such information is not available (except point data on snow depth and SWE), rather than selecting sites at which also other physical snow properties are measured. Suitable data would be available from various snow and avalanche research institutions in the European Alps that regularly collect and publish data on snow stratigraphy, profiles of density, microstructure, grain size and type, hardness, etc. at several sites and on several dates during winter. This would be a useful basis for assessing the response of Sentinel-1 backscatter signals and model performance in respect to specific snow properties. An excellent source of relevant snow and radar data (including Sentinel-1 time series and tower-based C-band radar measurements) is also the multi-year NASA SnowEx program. Authors of this manuscript contributed to this program.

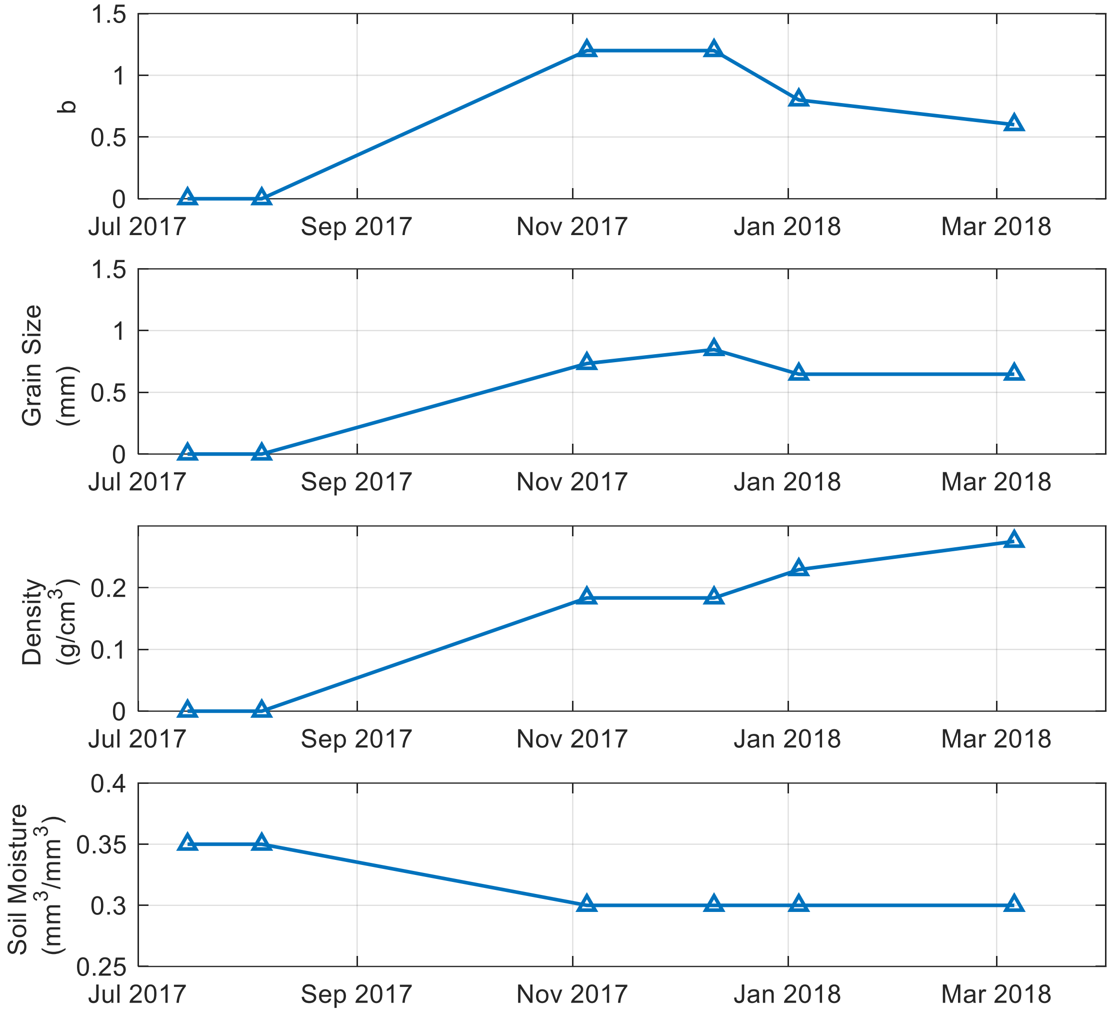
Thank you for pointing this out. The reason why these particular sites were chosen because our co-authors from the Belgium will do a complete SWE retrieval study of the area of the chosen sites and a few other. That study will use the physical models described in this paper to solve the inverse problem of retrieving SWE. As such, this paper is focused on evaluating the forward model at these Sentinel-1 sites and to physically explain the reason why Sentinel-1 data shows increased sensitivity to cross-polarization backscattering when SWE increases whereas co-polarized backscatter is relatively unchanged. This has been reported in many articles like Lievens et al 2019, 2022 and Hoppinen et al 2024. But they do not give a physical reasoning of this increase. Zhu et al. 2023 showed the physical modelling but did not test it with time series Sentinel-1 data. This paper explains the physical modelling with Sentinel-1 data on how the combination of volume and surface scattering results in the correlation of cross-polarization ratio to SWE. This paper uses SWE but the physical reasoning remains the same. This paper takes the hypothesis of Zhu et al and applies it successfully to the Sentinel-1 data. The goal was to explain the measured Sentinel-1 data with physical modelling of volume and surface scattering. The authors believed that it was more time efficient to use the same locations that will be used in all the studies and hence kept these sites. We realize that it meant using sites that lack detail in-situ measurements. The work shows that even in lack of detailed information about snow properties information, the model can show the trend of Sentinel-1 data which is important as satellite mission (current or future) may not have access to these detailed in-situ measurements. We corrected the issues with soil moisture in the comments below. Regarding inverting the model for retrieving SWE with many unknown snow parameters, we do not use the complete bi-continuous DMRT as is. We are developing a parameterized single layer bi-continuous DRMT model in which the different parameters of snow are condensed into just two. This results in a very simple model which lets us invert for the co-polarized and cross-polarized backscattered signal to SWE without detailed knowledge of snow parameters or prior information. The details can be found in Borah et al 2023. That work is for two frequencies of X and Ku band, we are modifying it to use for single frequency of C band with two polarization measurements. The work started sometime after this paper and could not be put into this paper. This paper focused on the forward model and physical explanation of the Sentinel-1 data. Quantitative analysis of these results and relating them back to the snow conditions for successful retrieval of SWE is being worked on by the co-authors from the Belgium group and those results will be explained in detail in future work. This explanation of site choice has also been added to the Section-2. Hope this make the authors choice clear to the reviewer and find it satisfactory.

The magnitudes and temporal evolution of the parameters used for model input (Fig. 10) are not in accordance with typical properties of snow and ground in high Alpine terrain of the European Alps. For example, the average size of the scattering elements of the total snowpack decreases during the main accumulation period as long as the snowpack is dry (Calonne et al., 2020). Of particular concern are also the assumptions regarding the soil moisture content. First, it should be mentioned that the selected sites, located in the Alpine tundra zone, are almost completely covered by Alpine grassland and only to a small part by bare surfaces. The soil moisture content in Fig. 10 is largely underestimated. For example, measurements at a Swiss station in 2450 m elevation throughout three years show that the 10 cm moisture content of soil never dropped below 20 vol % (Pellet and Hauck, 2017). In the European Alps major rainfall events up to high altitudes happen also during autumn, and transient melt events are common after the first snowfall. Throughout winter the soil at the snow ground /interface in the Alpine tundra zone of the European Alps contains liquid water because the ground heat creates conditions close to melting and the soil temperature is bounded at 0° C (e.g. Wever et al., 2014; 2015). The lack of a common temporal trend of sigma0 VV during the pre-snowfall and dry snow periods (Figs. 1, 2, 3) is in line with these observations. Furthermore, differences snow and soil properties between individual sites and years may also play a role.

The authors would like to thank the reviewer for pointing this information out. First, we would like to point that the sites that we have chosen for study are mostly bare surface with little Alpine grassland verified under satellite image. We have shown two locations here.



We corrected the soil moisture in accordance with Pellet and Hauck, 2017 which shows that the soil moisture is between 40 vol% to 20 vol%. We changed the soil moisture for the analysis of Figure 9. Now the soil moisture for snow free time starts at 35 vol%. Then the soil moisture goes down to 30 vol% and winter sets in. This results in the reduction of backscattered signal at co-polarization and cross-polarization as the data shows in Figure 1 and the model in Figure 9. Since there is little snow fall at this point the backscattered signal is from the surface scattering. A reduction in surface scattering component means reduced soil moisture. As the snow starts accumulating, as stated by the reviewer, the moisture is contained in below the snow pack, the soil moisture is kept at 30 vol% for the remaining of the dry winter period. Please note that, changes to the soil moisture meant adjusting the rms height of the bare soil surface. The revised rms height is now 0.8 cm. This is in accordance with the measured Sentinel-1 data. The updated parameter evaluation graph is shown below-



This parameter evaluation is only for the winter season of 2017-2018 for location 1 as shown in Figure 9. Different years and different loactions have different parameter evaluation conducted in a similar manner as this one but in accordance with the measurements of those years and locations. This has also been made clear in the manuscript in the paragrph between lines 281 till 293. Figure 9 and 10 have been updated in the manuscript but Figure 9 remains very same as the absolute backscatter from the rough surface scattering remains the same.

Specification regarding the satellite track and local incidence angle of the Sentinel-1 data at the 3 sites used for input data tuning, validation and shown in the figures is missing. Most areas of the European Alps are covered by Sentinel-1 IW mode data of four different satellite tracks, which means a single site is viewed within every 12-day period under four different incidence angles and two different aspect angles. In the paper it is not mentioned if the Sentinel-1 data shown in the figures and used in the study are obtained from a single track or are composites of multiple tracks. The incidence angle has a major impact on the partition between volume scattering and surface scattering contributions. Sentinel-1 data of different incidence angles can be used for checking the model performance in this respect.

Thank you for pointing this out. It has now been added in the Section-2 of the manuscript that: this study uses only one track of Sentinel-1 data, track 161. This keeps the incidence same. The reason for using this particular track is that the incidence angle is higher than 30 degrees most of the time. This incidence angle and higher values are more useful as the volume and surface scattering can be distinguished in the total scattering signal. This is because the rough surface scattering is specular scattering and decreases considerably as the incidence angle increases but the volume scattering is diffused scattering and remains relatively same for a wide range of incidence angle (Tsang et al 2001). At lower incidence angles, below 20 degrees, the volume and surface scattering signature may look the indistinguishable but at angles of 30 degrees and higher, the surface scattering drops down and make the two signal separate. The variation of incidence angle within this one track is 15 degrees and the model performs well.

Further comments:
Snow depth and SWE are used alternately in the paper. Please check the proper use of these terms and specify the respective data sources.

Thank you for pointing this out. All the terms have been corrected to SWE as the study is based on SWE. Snow pack is used when describing the snow conditions in the model used.

Line 47: Please explain to which airborne mission-s this statement refers.

It has now been added to line 47: “Although these recent airborne missions like the SnowEx campaigns and the AlpSAR campaigns…”

Line 52: Lievens et al (2019) refers to snow depth.

Thanks for pointing this out. It has been corrected.

Line 135-136: Please explain why these three sites have been selected, rather than sites with more comprehensive in situ snow observations that include information snow morphology, structure, stratification. Please provide specifications for the snow depth and SWE measurement sensors.

Please see the main comment for the reasons for site selection. It has been added in Section-2 that: “The SWE data used in the paper is based on modelled SWE. The data is coming from the SnowClim v1.0 process-based model of Lute et al. (2022) adapted with downscaled Multi-Source Weather (MSWX) and Multi-Source Weighted-Ensemble Precipitation, version 2.8 (MSWEP V2.8) data (Beernaert et al. 2023).” The SWE data has also been added to the data availability section as well.

Line 137: The surface cover of these three sites is dominated by vegetation cover (alpine grassland). This can be checked by means of very high resolution satellite imagery.

Please see the main comment on this.

Line 141ff, Figs 1 ,2, 3: Please provide details on the satellite data shown in these figures and used for validation (single track or merger of several tracks, temporal aggregation method (in case this is applied), local incidence angle, number of looks, radiometric calibration). Also, please explain if SWE in these figures is based on measured data or deduced from snow depth, using density estimates.

It has been added in Section-2: “This study uses only one track of Sentinel-1 data, track 161. This keeps the incidence same. The reason for using this particular track is that the incidence angle is higher than 30 degrees most of the time. This incidence angle and higher values are more useful as the volume and surface scattering can be distinguished in the total scattering signal. This is because the rough surface scattering is specular scattering and decreases considerably as the incidence angle increases but the volume scattering is diffused scattering and remains relatively same for a wide range of incidence angle (Tsang vol 2). At lower incidence angles, below 20 degrees, the volume and surface scattering signature may look the indistinguishable but at angles of 30 degrees and higher, the surface scattering drops down and make the two signal separate. The variation of incidence angle within this one track is 15 degrees and the model performs well. The SWE data used in the paper is based on modelled SWE. The data is coming from the SnowClim v1.0 process-based model of Lute et al. (2022) adapted with downscaled Multi-Source Weather (MSWX) and Multi-Source Weighted-Ensemble Precipitation, version 2.8 (MSWEP V2.8) data (Beernaert et al. 2023).”

Line 144: Please specify the source of information on snow density for relating snow depth and SWE.

In line 144 has been changed to: “The SWE in these regions consistently cross more than 0.6 m (snow depth more than 2 m, based on volume fraction of 30% ice).”

This is done only for illustrative purposes to show the reader how deep the snow is in both SWE and snow depth. 30% volume fraction of ice is a large case scenario.

Line 161, Fig. 4 and volume scatter simulations: The term on ground-surface/volume interaction is missing.

It is now added in line 166: “The ground surface interaction is not included in Figure 4 as equation 1 is based on first order scattering between the snow volume and ground surface. Ulaby 2015 shows that the majority of scattering comes from first order term.”

Line 193 ff: The microstructure representation and derived bi-continuous media formulation should be related to actual observations of microstructure in high Alpine snowpacks and in which way the variations between individual snow layers are taken into account.

As mentioned in lines 285-286, a single layer snow pack model is used in this work. Which means we need to use effective average parameters which will give same backscattered signal as that of the multilayer model.

Line 225ff, Rough soil surface scattering: The selected soil roughness and dielectric properties do not match the specification of vegetated surfaces, as the case for the three test sites which are covered by Alpine grassland (see main issues).

Please see the main comments.

Line 262 and Table 1: Please specify the incidence angle to which the backscatter values refer.

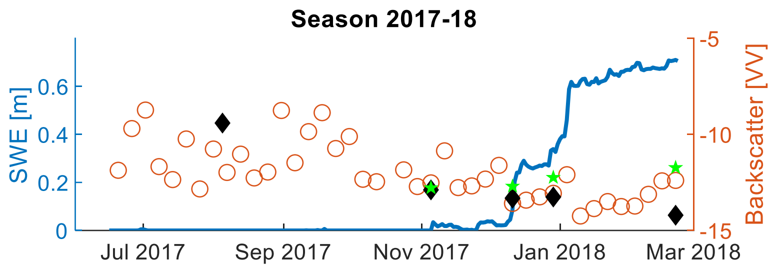
It is now added: “The incidence angle used of the simulations is 40 degrees.”

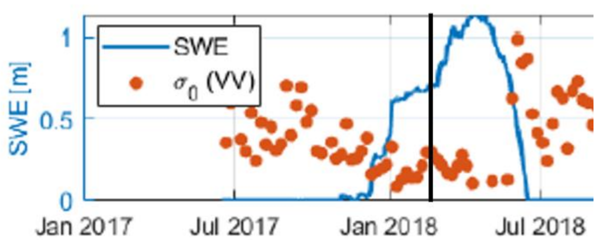
Figure 8: Results for different incidence angles would be of interest.

The results for different incidence angle can be found in Zhu et al 2023 and 2024. It has been added in the manuscript.

Figure 9: Please specify on which Sentinel-1 tracks and sites the sigma0 values are based. Data for season 2017-18 are shown here during which sigma0 shows a different behaviour in the snow accumulation period than in the other years (in particular at point 1).

The track has been detailed in Section-2. The data is exactly the same between Figure 1 and Figure 9. It looks stretched out because of the scale. The data in Figure 9 ends on 21 March as indicated in line 266 (dry snow).





Line 282ff and Fig. 10: Please explain why sites without in-situ snow microstructure were selected. In order to obtain model input data, a tuning exercise may end up with data on the snowpack and ground that do not match actual properties of snow structure and the ground (see main issues).

Please see the main comments.

Line 286ff: Since September 2015 on SMAP only the microwave radiometer with a footprint size of 39 km x 47 km has been working. Barely the scale for deriving soil moisture and permittivity for sites of 100 m extent in mountainous terrain. Regarding the assumptions for soil moisture content see main comments.
As commented by the reviewer this has been removed and the explanation in the main comment regarding soil moisture has been added to the manuscript.

Line 299: The statement "Cross-pol on the other hand is much more sensitive to volume scattering as cross-pol rough surface scattering is much lower compared to co-pol" is not in accordance with the sigma0 data shown in Figs 1, 2, 3. At sites 1 and 2 sigma0 VH is of similar magnitude during the snow-free and dry snow periods.

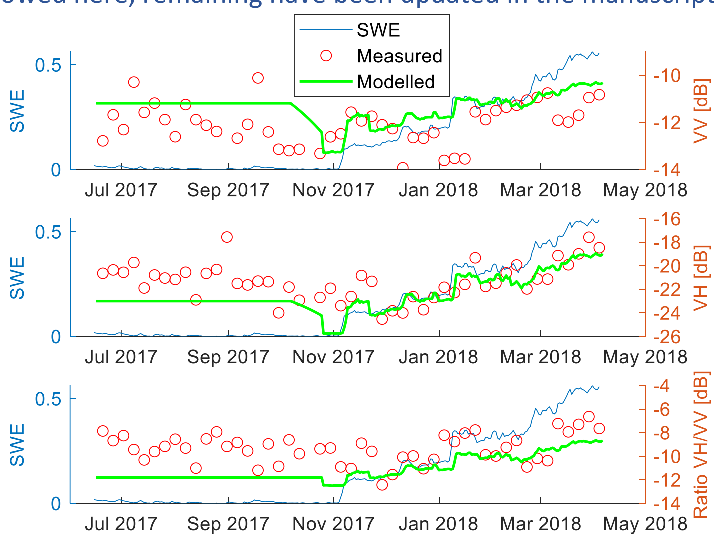
Line 299 has been made clearer: "Cross-polarization is more sensitive to volume scattering as cross-polarization rough surface scattering is much lower than the co-polarized rough surface scattering."

The comparison is between the different polarizations of the volume and surface scattering component at the same time. Table 1 shows that for the dry snow period, the cross-polarized backscatter increases from -25dB to -19dB whereas co-polarization backscatter is about -12dB. Snow free observations are useful to quantify the parameters for the rough surface scattering part as stated in lines 287-290. But are not used to study the properties of the snow. Even though sigma0 VH may show similar magnitude between snow free and dry snow period, we are interested in the increase of the VH backscattered signal in the dry snow period, which can also be seen in Figures 1, 2 and 3.

Figures 11 to 14: The comparisons of computed and measured sigma0 and the related discussion in the text are not conclusive. Data of different seasons are shown for the individual sites: 2017/18 for point 1, 2018/19 for point 2, 2017/18 and 2018/19 for point 3. Showing data of all years and also related snow depth time series is recommended.

Because the analysis was done for the dry snow period, the authors feel like putting the years in one single graph will have gaps when the snow becomes wet and till the snow free analysis for the next year starts and not like a continuous graph of measured data in Figures 1, 2 and 3. This may take away from the model performance emphasized in one year which shows how the model behaves with the Sentinel-1 data and explains the data. That is why each seasonal year was done separately. The four figures of Figure 11 to 14 also show that the model can be applied to the remaining years as well.

The authors added the SWE data to the Figures 11-14 so that the analysis is clearer. One figure is showed here, remaining have been updated in the manuscript.



Line 303 ff: For evaluating model performance, quantitative statistical analysis needs to be performed. For comprehensive assessment it is also necessary to show comparisons with backscatter data that are not used for tuning the model input parameters.

The reasons of not including quantitative analysis of the model are because of 100m resolution as indicated in the manuscript is so spatial variability is minimized. Another one is that using 100m resolution means using 100m land area for rough surface scattering simulations. This is possible with the current NMM3D model described. But increasing the area to 500m significantly increases the complexity of the problem from an electromagnetics point of view. It is true to remove the aspects speckle, elevation and slope a larger area is recommended and the authors are working on a new rough surface model that will be able to handle larger areas with slope and elevation change by using fractal surfaces. Future analysis will include that model. The current rough surface model assumes a flat surface. This is one of the main reason this paper focused more on physically explaining the Sentinel-1 data with the best possible models available at the time of writing this manuscript and this does not include quantitative analysis of measured and modelled data at the end. The authors believe that with fluctuations due to 100m resolution will not result in accurate quantitative results. The general trend of the data is very much visible which was the important part of the work. This is also made clear in the Section 4 and Conclusions as well. Point by point quantitative analysis of these results and relating them back to the snow conditions for successful retrieval of SWE is being worked on by the co-authors from the Belgium group and those results will be explained in detail in future work using these improved models.

References:

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