Comments on: Time Series Analysis of C-Band Sentinel-1 SAR Over Mountainous Snow with Physical Models of Volume and Surface Scattering

By Borah F.K., J.-F. Jans, Z. Huang, L. Tsang, H. Lievens, and E. Kim.

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.

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.

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.

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.

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

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

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.

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.

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.

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

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

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.

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).

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

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

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).

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).

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.

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.

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.

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.

References:

Calonne, N., Richter, B., Löwe, H., et al.: The RHOSSA campaign: multi-resolution monitoring of the seasonal evolution of the structure and mechanical stability of an alpine snowpack, The Cryosphere, 14, 1829–1848, 2020.

Pellet, C. and Hauck, C.: Monitoring soil moisture from middle to high elevation in Switzerland: set-up and first results from the SOMOMOUNT network, Hydrol. Earth Syst. Sci., 21, 3199–3220, 2017.

Wever, N., Fierz, C., Mitterer, C., Hirashima, H., and Lehning, M.: Solving Richards Equation for snow improves snowpack meltwater runoff estimations in detailed multi-layer snowpack model, The Cryosphere, 8, 257–274, 2014.

Wever, N., Schmid. L., Heilig, A., Eisen, O., Fierz, C., and Lehning, M.: Verification of the multi-layer SNOWPACK model with different water transport schemes, The Cryosphere, 9, 2271–2293, 2015.