

The Cryosphere Discuss., author comment AC2
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Reply on CC2

Hans Lievens et al.

Author comment on "Sentinel-1 snow depth retrieval at sub-kilometer resolution over the European Alps" by Hans Lievens et al., The Cryosphere Discuss.,
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We thank Helmut Rott for providing important feedback and comments to our manuscript. Please find below an initial response to the comments, which we'll further address during the revision.

Comment: "The objective of the work, promoting the wider use of operational SAR data for snow monitoring, is a very relevant undertaking, in particular as the spatially detailed monitoring of snow depth and mass in areas of complex topography is an open issue. However, as mentioned by the reviewers, the physical basis of the presented method is not clear. On page 5, line 17, the authors explain that the method is based "on the physical principle of an increase in snow volume scattering with increase in snow depth". I am not aware of any physical principle relating the radar backscatter intensity of a snow-ground medium to snow depth. As thoroughly proven by theory and experimental studies, the magnitude of the volume scattering signal of snow is largely determined by the size, shape and distribution of the scattering elements and their relations to the radar wavelength (e.g. Tsang et al., 2013). For backscatter modelling the description of the complex microstructure of snow as a sintered medium is critical (Löwe and Picard, 2015). The diversity of snow microstructure is probably a reason for the large spread of the scaling factor for converting the snow index to snow depth, changing according to Figure 7 by about one order of magnitude from low to high elevations."

Authors response: We agree that the exact physical principles of snow scattering at C-band are not yet fully understood and require further investigation. Therefore, this work focuses on the use of observations in an empirical change detection retrieval approach. The snow microstructure, i.e., the size, shape and distribution of the snow crystals, can indeed have an important impact on the scattering. But, also the amount of snow crystals, which is related to snow depth, will have an important effect. The physical principle noted in the manuscript refers to the fact that more snow crystals (a thicker snowpack) will generally increase the scattering (especially in cross-pol and subject to a dry state of the snow, as demonstrated in Figs. 3-5). We will better articulate this in the text upon revision. Furthermore, other structural snowpack properties could have an effect especially at lower frequencies (e.g., C-band compared to Ku-band), such as the anisotropy of individual crystals, or more likely of clusters of crystals, and the stratigraphy (as rightly pointed out by reviewer 1). Identifying the impact of these snow properties is recommended for future investigation. In this context, Prof. L. Tsang (University of Michigan) is currently investigating the radiative transfer modeling of snow at C-band,

accounting for the effects of snow layering and clustering. Preliminary results are supporting the Sentinel-1 observations, by showing an increase in backscatter of a few (2-3) dB with an increase in SWE to 300 mm, primarily in cross-polarization (personal communication with Prof. L. Tsang).

Overall, the spatially dynamic scaling factor has a limited impact on the snow depth retrievals (i.e. only a small improvement; see Fig. 8). Between elevations of ~ 1000 m and 3000 m, the scaling factor varies only moderately, from ~ 0.9 to ~ 1.2 . The strong variation at low elevations (< 1000 m) is driven by the slight overestimation of shallow snow depths in the valleys. Note that a large difference in scaling factor will still only cause a small absolute difference in the case of a low value that is being rescaled. The strong decrease for high elevations (> 3000 m) was found to be caused mostly by glaciated areas, where the radar signal shows a strong increase during winter that is likely not only caused by changes in the snowpack. We will exclude glaciated areas for the calculation of the scaling factor during the revision to improve this aspect. Differences in snow microstructure with elevation can play a role, but addressing these impacts will be the subject of future investigation (including tower measurements, radiative transfer modeling and snow microstructure measurements).

Comment: "In order to learn about the impact of physical snow properties and microstructure on the backscatter signals and to test the retrieval algorithm, we tried to retrace the processing steps described in the manuscript, based on Sentinel-1 data and snow measurements in an Alpine test site. However, we could not proceed due to missing information, in particular regarding the procedures related to equations 2 and 5. Equation 2 describes the bias correction for σ_0 of a particular orbit and date in which the average σ_0 from different orbits and the temporal mean backscatter of the individual orbit are decisive factors. It is not specified to which time span the temporal mean refers. Regarding the calculation of the statistical numbers, I assume backscatter intensity values in linear scale are used, as required for statistical analysis."

Authors response: For Equation 2, the mean and standard deviation of the backscatter are derived from the full time series (Aug 2017 through July 2019; excluding the months of March to June). The bias correction is performed in dB scale, as this scale is also used in the change detection algorithm. Note that the distribution function of backscatter in linear scale has long tails, which could otherwise have a confounding impact on the bias correction. We strongly appreciate your effort to investigate the observed increase in backscatter with snow accumulation. We are open to provide support or exchange ideas, and would encourage to investigate this backscatter increase also in a spatial context (not only for one or few in situ sites).

Comment: "Equation 5 describes the relation (CR ratio) between cross- and co-polarized σ_0 . The cross-polarized ratio in dB (logarithmic scale) is multiplied by a constant factor ($A = 2.0$) in linear scale. This would yield a very low value for the first term on the right hand side of Eq. 5 and thus result in a large difference between the cross- and co-polarized terms. Possibly there is a syntax error, and A should be specified in logarithmic scale, yielding a shift by 3 dB for the first term. However, it is unclear why a constant value of 3 dB should be added to the σ_0 -VH values, in particular as subsequently the temporal changes in the snow index are clipped or reduced in order to avoid impacts of large changes in CR."

Authors response: We are aware that the cross-ratio (VH/VV) originally used in Lievens et al. (2019) was somewhat more intuitive than the rescaled version presented in this manuscript. However, we observed that the rescaled version improved the performance. Equation 5 is applied in dB scale. Therefore, multiplying the VH component by 2 indeed causes low values. However, this is not a problem within the empirical change detection algorithm. To the contrary, the factor 2 enhances the temporal variability in the VH

component, which results in a better retrieval performance.

Comment: “Essential components of the retrieval algorithm are the bias corrections and the spatial and temporal averaging procedures. The assumptions and rules related to these processing steps are hard to capture. In order to improve the traceability it would be helpful getting a concise account on these procedures in tabular and graphic form. This should cover the technical or physical constraints for subdividing the observations into true and biased values, as well as the various temporal and spatial merging and averaging procedures applied in the subsequent processing steps.”

Authors response: Bias correction methods are standard procedure in many remote sensing, modeling and data assimilation applications. We here perform a simple bias correction of the first two order moments (mean and variance) of the backscatter data between different Sentinel-1 relative orbits. The only temporal averaging that is performed is the calculation of weekly average backscatter. The spatial aggregation is performed by linearly averaging the snow depth retrievals from 100 m to 300 m and to 1 km. The prior spatial aggregation of the backscatter data (from ~20 m to 100 m) during the preprocessing is appropriately performed in linear scale.

Further comments:

Comment: “Page 5, line 18: Hard to understand why the Sentinel-1 data are used for retrieving the snow depth but not for detecting the snow extent. If a reliable signal on snow depth is available, this implicitly should account for the presence of snow. Besides, the selected optical snow extent product has 1 km resolution, not suitable for capturing the complex pattern induced by topography.”

Authors response: Early snow cover can be relatively shallow or wet (decreasing the backscatter in this case) and the difference with the snow-off backscatter can therefore be ambiguous. Gradually, during the snow accumulation, we observe a corresponding backscatter increase primarily in cross-pol, offering a mechanism for snow depth retrieval. The Sentinel-1 snow depth retrieval algorithm relies on a *time series* change detection and is not an algorithm for *spatial* snow-on or snow-off detection. Snow cover observations at the corresponding 100 m resolution would indeed be better suited for input use in the retrieval algorithm. However, the currently existing data at 100 m (or finer) have temporal gaps due to cloud cover, or include a gap-filling over relatively long time periods with no observations, increasing the uncertainty. The 1 km IMS snow cover data merges different input data sources with quality control procedures to ensure daily coverage. In the future, the use of higher-resolution snow cover data is expected to improve the retrieval performance.

Comment: “Figure 2 (page 8): According to this figure most of the stations in the Eastern Alps of Austria are either in valleys or in lowlands, including many sites within inhabited areas. This impairs the comparison in Alpine terrain.”

Authors response: We agree. Likely, an improved performance would be obtained when relatively more measurement sites would be located at higher elevations with deeper snow. A comparison with other grid-scale reference data (in addition to the model simulations used here), such as lidar snow depth retrievals, is foreseen in the near future.

Comment: “Figure 4 (page 12): In the plots (a, b, c, d) different scales are used for the y-axis in respect to σ_0 . For example, the scaling factor ($\Delta y / \Delta \sigma_0$ VH) in plot (b) is 0.6 times the factor used in plot (a), adjusted in order to achieve good visual agreement between σ_0 and snow depth in both cases. Actually there is a major difference in the VH backscatter response to snow depth between both sites, though being located at similar altitude.”

Authors response: The scale bars have been adjusted to enhance the visual interpretation. We will clearly mention this in the revised version. Note that the input used in the change detection method is a combination of the different polarizations. Therefore, it is not advised to directly relate the dynamic range in backscatter for one polarization with the dynamic range in snow depth. Fig. 8 shows that, in general, the spatial distribution in snow depth agrees well between Sentinel-1 retrievals and model simulations.

Comment: "Sections 3.2 and 3.3, correlations: There are two issues calling for further explanations. (i) It is mentioned repeatedly that spatio-temporal correlations were computed. This implies multiple correlation in which one dependent variable is related to two predictive variables representing temporal, respectively spatial, components. Details on the individual relations and their weights regarding the combined prediction of the dependent variable should be provided. (ii) In particular for snow depth larger than 2 m the correlation with in situ snow depth (shown in Fig. 11) is very high whereas the density plots in Fig. 10 show large scatter and a substantial bias. Possibly the correlations shown in Fig. 10 are based on a different sample?"

Authors response: Our intention is to show to the fullest possible extent the correspondence between the retrievals and in situ measurements. Therefore, we made density plots that include all available measurements and retrievals. Note that the temporal correlations between retrievals and measurements are separated from the spatial analysis in Fig. 11. To further clarify, this figure panel (a) shows the average and standard deviation of the time series correlation coefficients obtained for all individual sites. We agree that for some sites, underestimation occurs especially for large snow depths (shown in Fig. 11b). This could be caused by limitations of the algorithm, or by (undetected) wet snow, or spatial representativeness differences.

References:

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Tsang, L., K. H. Ding, S. Huang, and Xu, X: Electromagnetic computation in scattering of electromagnetic waves by random rough surface and dense media in microwave remote sensing of land surfaces, *Proc. IEEE*, 101 (2), 255–279, 2013.