Answer to the Anonymous Referee #1 – Manuscript tc-2019-175

This paper tries to link the backscattered signal of C-Band SAR Sentinel-1 data to the main 3 melt periods in alpine regions: moistening, ripening and runoff. This work is also supported by physical snow modeling using SNOWPACK and in-situ dataset from5 different monitoring stations in the Alps. I really appreciate the physics based explanation of σ^0 *variations.*

We thank the anonymous Reviewer for his/her positive comments.

That being said with the information in this manuscript, it is really not clear to me how the authors generated the "theoretical" curves of figure 5. More explanation and details on how the authors generated those curves is needed. What input data was used?

Another important factor which might be linked to the previous comment is that it seems the authors used the behaviors observed at the fives sites to describe the theoretical curves generated and used to create their approach to detect the 3 main melt phases. The authors then use those same sites to validate the approach, which I find redundant. The authors would need independent data to validate the approach. This would not be needed if the approach was based on theory of σ^0 *behaviors and those behaviors are observed in the S-1 data. Again, I feel like the curves generated in figure 5 need better explanation. Nonetheless, the authors seem to understand the different radiative transfer interaction of the microwave signal with the different snowpack properties.*

It would have been nice to see some radiative transfer modeling from SMRT or a similar RT model to simulate the σ^0 *behavior.*

We are thankful to the Reviewer to point out this critical issue allowing us to better clarify it. Figure 5 is an illustrative representation of the phenomenological relationship between the multi-temporal backscattering and the snow evolution during a hydrological year. It should not be considered as a "theoretical" curve, but more as a conceptual scheme to better illustrate our interpretation of the backscattering signal in the sites we considered.

The conceptual backscattering curve was derived by taking into account both the real observations of S-1 data and the main backscattering mechanisms reported in the literature. In detail, the first phase is related to the initial moistening of the snowpack. During the moistening the value of LWC is low and therefore the SAR backscattering experiences a significant decrease in its value (Shi and Dozier, 1995, Ulaby et al., 2015, Nagler and Rott, 2000, Magagi et al. 2003). During the moistening, the wetting front may be visible only during the afternoon and not in the morning since the snowpack is still subjected to the diurnal cycles of melting and refreezing. As soon as the wetting front has penetrated the superficial insulating layer of the snowpack, the wet snow becomes visible also in the SAR early morning acquisitions with a significant decrease of the backscattering. This condition can be used to identify the start of the snowpack ripening phase. During the ripening phase, which is influenced by the weather and the snowpack conditions, σ^0 varies according to the snow conditions but with an overall decreasing trend due to the increase of LWC (Shi and Dozier, 1995, Ulaby et al., 2015). We observed that the minimum of σ^0 is reached in correspondence of the finishing of the ripening phase and the beginning of the run-off phase for all the ten time series observed (see section 5). The run-off phase is instead characterized by a monotonic increase of the backscattering till all the snow is melted. To our knowledge, this characteristic behavior has never been observed in the literature before. Our interpretation is as follows: when the considered snowpack reaches its saturation condition in terms of LWC and snow structure, the backscattering recorded in C-band reaches its minimum value. This snowpack condition seems to correspond with the isothermal condition i.e., the end of the ripening phase. After the saturation point is reached, the monotonic increase of σ^0 could be explained by one or the combination of the following factors: i) an increase of the superficial roughness (Shi and Dozier, 1995, Magagi et al. 2003); ii) a change in the snow structure i.e., increase of the density and increase of grain size (Shi and Dozier, 1995, Ulaby et al., 2015) and; iii) at the end of the melting, the presence of patchy snow creates a situation of mixed contribution inside the resolution cell of the SAR and therefore a further increase of the total backscattering is recorded.

From the generalized behavior derived by considering both the observations and the EM background, we derived a set of rules to be applied to the time series of backscattering (that we report in pseudocode in Figure 1b). In order to understand the effectiveness of the proposed rules, they were applied to 1-dimensional cases, made up of the 5 different test sites and the 2-dimensional case of the Zugspitze catchment. In detail, we compare the time onsets derived by the proposed set of rules and the same onsets derived using the algorithm reported in pseudocode in figure 1a from independent measurements of LWC and SWE. This comparison is now discussed in deeper detail as suggested from the Reviewer 2.

The same set of rules has been applied to the 2-dimensional case of the Zugspitze catchment. In this case, a selection of time series of backscattering was randomly selected from the pixels in the Zugspize catchment that were never been used before and reported in Figure 6c of the paper. As one can notice, the characteristic behavior described in section 4.2 is well recognizable.

Finally, it is worth mentioning that from a recent work by Veyssière et al., 2019 (that was not cited in the current version of the manuscript) it is possible to appreciate the classical "U-shape" described in our article derived from an independent dataset ,where S-1 observations were available together with SWE and LWE (simulated). Qualitatively, our proposed rules for the identification of the snow melt phases can be applied also in this independent dataset.

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Algorithm 1: Identification of the melting phases
  Input: Liquid Water Content LWC and Snow Water Equivalent SWE observations for a given day
         d, d ∈ {1, 2, ..., D} with D total number of days with SWE > 0, SWE_max
  Output: Onset moistening T_M, onset ripening T_R, onset runoff T_RO
  while d ≤ D do
      if LWC_max,d > 0 kg/m^2 then
          # Snowpack is wet
          # Check moistening phase
          if (LWC_max,d > 1 kg/m^2) and (LWC_min,d = 0 kg/m^2) for at least 2 days then
              T_M = d
              # Do not check this condition anymore
              continue
          end
          # Check ripening phase
          if (LWC_max,d > 5 kg/m^2) and (LWC_min,d > 0 kg/m^2) then
              T_R = d
              # Do not check this condition anymore
              continue
          end
          # Check runoff phase
          if (SWE_d == SWE_max) then
              T_RO = d
              # Do not check this condition anymore
              continue
          end
      end
      else
          # Snowpack is dry
      end
      d ++
  end
```

(a)

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Algorithm 2: Identification of the melting phases
Input: Multitemporal backscattering observations for different tracks, σ_morining and σ_afternoon, for
       a given day d, d ∈ {1, .., d, .., D} with D total number of observations
Output: Onset moistening T_M, onset ripening T_R, onset runoff T_RO
while d ≤ D do
  if σ_afternoon,d − σ_dry ≥ −2 dB then
    # Snowpack is wet
    # Check moistening phase
    if (σ_morning,d − σ_dry < −2 dB) then
      T_M = d
      # Do not check this condition anymore
      continue
    end
    # Check ripening phase
    if (σ_morning,d − σ_dry ≥ −2 dB) then
      T_R = d
      # Do not check this condition anymore
      continue
    end
    # Check runoff phase
    if (σ_d ==σ_min ) then
      T_RO = d
      # Do not check this condition anymore
      continue
    end
  end
  else
    # Snowpack is dry
  end
  d ++
end
```

(b)

Figure 1 Algorithms used for the identification of the melting phases from: (a) LWC and SWE; and (b) S-1 time series of backscattering.

We agree that a proper EM modeling would strengthen Figure 5, which is now based on real observations and on the literature background. This has been investigated during the work that lead to the present form of the manuscript. Nonetheless, after identifying some crucial limitations of both i) the current RT models in modeling the snowmelt process (especially the runoff conditions as reported later in the review); and ii) the lack of ground truth information on some important snow parameters in the considered test sites (i.e., snow superficial roughness and internal structure during the three melting phases), we favored to present our analysis using the observations of real data and the rich background literature. This in our opinion allowed a quick dissemination of the results obtained in the paper, which has been proved to be reproducible.

However, we would like to show and discuss the SMRT (Picard et al., 2018) results to highlight the limitations of the model to explain the real S-1 behavior of Figure 4 (and therefore of Figure 5), especially during the melting. This is the main motivation why we would like not to include such analysis in the current version of the paper. However, we aim to include the radiative transferring modelling in a future paper. Below we present our preliminary results using the SMRT formulation, which, we believe, confirm the assumption we did in the present paper.

In detail, we consider a simplified one-layer snowpack, derived by averaging the proprieties of the snowpack simulated for Malga Fadner in the hydrological year 2017-2018 by SNOWPACK. Similar conclusions can be repeated for any of the five test sites considered in the paper and for any of the hydrological years. The improved Born approximation (IBA) with sticky hard spheres microstructure, was used together to the discrete ordinate and eigenvalue radiative transfer (DORT) solver in order to simulate the backscattering coefficient at 5.405 GHz at 34 degrees incidence angle. This SMRT formulation was demonstrated to produce equivalent results of DMRT-based models (Picard et al., 2018).

Following the empirical approach elaborated in Brucker et al., 2010 and Picard et al., 2014, we used non-sticky spheres (i.e., infinite stickiness parameter) and scaled the radius computed from SSA by an empirical factor phi (called "grain size scaling factor"). This was obtained by fitting model results to real Sentinel-1 measurements during the accumulation period. We parametrized the substrate as a reflector providing constant backscattering of -12 dB at VV and -20 at VH (according to what observed in average in dry/frozen conditions).

Figure 2a shows the obtained results. As one can notice SMRT is accurately modeling the backscattering during the accumulation period. But, as soon as the snowpack is getting wet, large differences are visible from the modeled and measured backscattering. The differences are less pronounced in VV than in VH. Interestingly, as in the real S-1 data, an increase in the backscattering is visible after the maximum of SWE is reached. This is mainly due to the grain coarsening during the snowmelt metamorphism. This can be verifying by simulating the same time series with a constant grain size (see Figure 2b). Therefore, it is not clear if there is only a problem of scale (e.g., proper parametrization of the grain size) or some contributions to the backscattering are not considered in model. In particular among the several reasons that can be credited to this behavior we identified:

1. During the snowmelt process, the melt forms tend to group together generating clustered grains with large size;
2. Possible contributions to the total backscattering are not taken into account. In particular, as identified in the manuscript, the contribution by the increasing superficial roughness during the snowmelt should be considered in the model.
3. The value of LWC modeled by SNOWPACK can be overestimated in the considered simulations.

In the following we address in detail the first two points. Whereas for the last point, not having a real ground truth, we can only say that the values seem to be in a reasonable range w.r.t. other alpine snowpacks (Koch et al., 2019, Koch et al., 2014, Heilig et al., 2015, Techel et al., 2011).

As mitigation of point 1, we tried to optimize phi so that to reach the values observed by S-1 during the melting. Even though increasing phi has the effect of increasing the backscattering, it was not possible to converge to a suitable phi. In fact, we reached a point for which the integral of the phase matrix was larger than the scattering coefficient (i.e., the grain size is too big compared to the wavelength before obtaining from the simulation values comparable to the observed values). This suggests that the grain size may be not the only contributor to the total backscattering, and other variables e.g., the superficial roughness, may play a not negligible role.

For point 2 we investigate the possibility to implement the superficial roughness in SMRT. This can be done thanks to the modularity of the code. As discussed in the paper, at the best of our knowledge, only few works have been presented that model the wet snow with active sensors at C-band i.e., Shi and Dozier, 1995; Longepe et al., 2009 and Magagi et al. 2003, Veyssière et al., 2019. Beside the recent work of Veyssière et al., 2019, they are not taking into account the snow microstructure distribution. Even though, in Shi and Dozier, 1995 a deep study of the backscattering mechanisms was conducted with their model, which indicate a positive correlation between largely wet snowpack and the superficial roughness (similar considerations can be found in Magagi et al. 2003), Kendra, Sarabandi and Ulaby, 1998, on the basis of experimental analysis, expressed some doubts on the realism of such model. Therefore, this research topic requires a dedicated effort and validation campaigns that are out of the scope of this paper and it will be left as future work. This also because continuous measurements of snow roughness are unavailable at the moment.

In summary, for answer the Reviewer question, by using state-of-the-art simulation (i.e., SMRT) it has been possible to partially confirm what already known from the literature, but it did not add a full understanding of the backscattering mechanism, especially in the runoff phase, which in our opinion requires further research. In detail the simulations confirmed:

1. For low amounts of free liquid water in the snowpack, the high dielectric losses increase the absorption coefficient and reduce the recorded backscattering (Shi and Dozier, 1995, Ulaby et al., 2015, Nagler and Rott, 2000).
2. The increasing in grain size has a positive correlation with the volumetric backscattering (Shi and Dozier, 1995, Ulaby et al., 2015), which can be relevant during the melting.
3. The contribution from the ground in general dominates the total backscattering in dry conditions (Rott and Matzler, 1987, Shi and Dozier, 1993) but it is hidden when the snowpack is in wet conditions (Ulaby et al., 2015, Ulaby and et al., 1984).

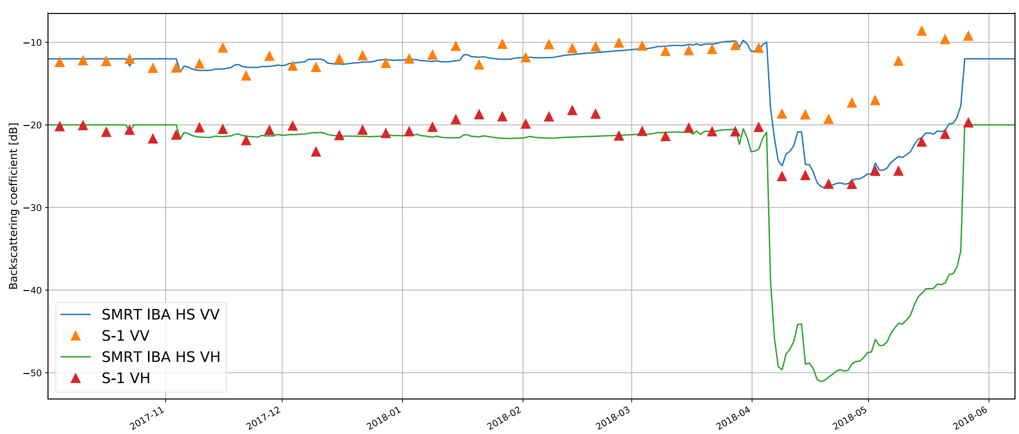
To incorporate this comment in the paper, section 4.2 has been re-entitled as follows

“Illustrative temporal evolution of backscatter”

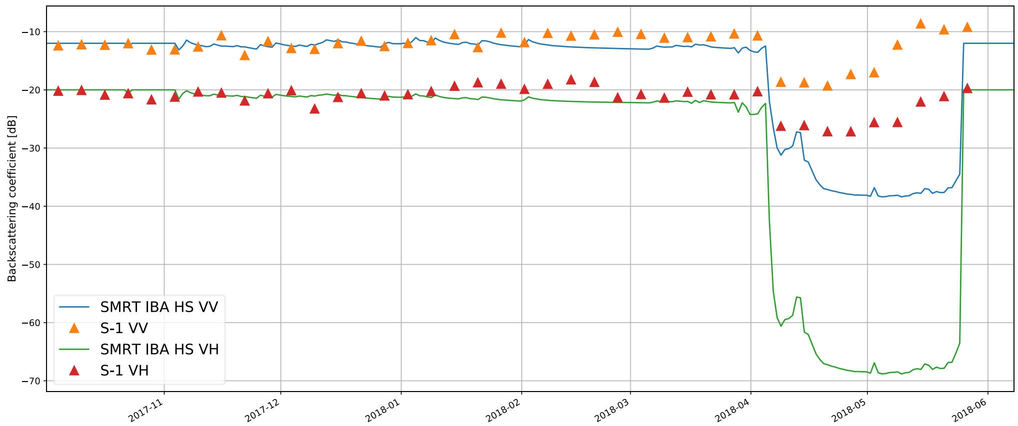
Section 5 has been renamed:

“Application of the proposed approach in 1-D and 2-D cases”

and an exhaustive discussion on the limitations of the state-of-the-art model and the lack of validation data during the melting period (e.g., time series of snow roughness) have been added to the paper.



(a)



(b)

Figure 2 SMRT simulated backscattering coefficient compared with S-1 acquisitions. (a) the grain size has been derived from SNOWPACK simulation; and (b) the grain size has been considered constant to 0.5 mm during all the time interval of the simulation.

Additional references not reported in the manuscript for answering this question.

Brucker, L., Picard, G., Arnaud, L., Barnola, J., Schneebeli, M.,Brunjail, H., Lefebvre, E., and Fily, M.: Modeling time series of microwave brightness temperature at Dome C, Antarctica, usingvertically resolved snow temperature and microstructure mea-surements, J. Glaciol., 57, 171–182, 2011a.

Heilig, A., Mitterer, C., Schmid, L., Wever, N., Schweizer, J., Marshall, H.-P., and Eisen, O. (2015), Seasonal and diurnal cycles of liquid water in snow—Measurements and modeling, J. Geophys. Res. Earth Surf., 120, 2139– 2154, doi:10.1002/2015JF003593.

Picard, G., Royer, A., Arnaud, L., and Fily, M.: Influence ofmeter-scale wind-formed features on the variability of the microwave brightness temperature around Dome C in Antarc-tica, The Cryosphere, 8, 1105–1119, https://doi.org/10.5194/tc-8-1105-2014, 2014.

Picard, G., Sandells, M., and Löwe, H.: SMRT: an active–passive microwave radiative transfer model for snow with multiple microstructure and scattering formulations (v1.0), Geosci. Model Dev., 11, 2763–2788, https://doi.org/10.5194/gmd-11-2763-2018, 2018.

Veyssière, G.; Karbou, F.; Morin, S.; Lafaysse, M.; Vionnet, V. Evaluation of Sub-Kilometric Numerical Simulations of C-Band Radar Backscatter over the French Alps against Sentinel-1 Observations. Remote Sens. 2019, 11, 8.

Ulaby, F. T., Stiles, W. H. and Abdelrazik, M., Snowcover Influence on Backscattering from Terrain, in IEEE Transactions on Geoscience and Remote Sensing, vol. GE-22, no. 2, pp. 126-133, March 1984. doi: 10.1109/TGRS.1984.350604

Specific comments:

L.5. Remove "be" in "to be obtained".

L.51. Change "The establishing"

L.76. change "has demonstrated" to "was shown"

L.94-95. This nominal resolution is only true for the high res IW mode. It can be removed in this section of the text since it is better described in the data section.

L.98. Remote "the" in "the monitoring"

L.106. change "polarimetric" to "polarization"

L.144. correct "properties"

L.171. remove "round the grains", metamophism does not always round the grains, more complex shapes can be created. Simply remove this part.

L.187. change to "October 1, 2016"L.280. correct "removal"

L.411-412. not clear to me what you mean by depolarization here. To me depolarized signal implies that the V transmit is switched to H thus increasing VH and decreasing VV. An ice layer alone would not depolarize your signal, it would affect the scattering by adding a reflective layer in your snowpack.

We thank the Reviewer for pointing out these editorial comments that we will correct in the revised version of the manuscript accordingly.