Reply to comments from Reviewer 2

Montpetit et al.

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1 General Comments

The study presents an experiment simulating radar backscattering intensity of snow-covered ground in a tundra environment using a coupled ground-snow radiative transfer model. Model simulations, driven by a combination of pre-retrieved and measured parameters, are compared to backscattering at Ku-band measured by an airborne radar instrument. Ground properties defining surface backscattering are retrieved from satellite-based measurements at lower frequencies, using these to guide the Ku-band retrievals. The forward simulation setup is used to retrieve optimized values for snow polydispersity in a two-layer simulation setting.

The text is generally well written and clear, and the subject is of high interest to the community since it provides new insight into the recently proposed concept of microwave grain size and how this is related to radar backscatter observed in remote sensing. However, I feel the section describing the forward model setup is currently insufficient to fully comprehend the experiment, with some details explained only in the discussion. The origin and use of structural polydispersity, a key aspect of the paper, is not fully explained, nor how this is used together with measured optical grain size to calculate the scattering coefficient in radiative transfer. Furthermore, some measurements such as those on soil permittivity, are meticulously presented but finally not used anywhere in the paper. Likewise, it is unclear how snow pit measurements were finally used in the simulations. These aspects should be improved before considering the paper ready for publication. Please see detailed comments below.

Figures are clear and present the results in a useful way, although figure captions are on occasion too concise to fully describe the figure contents. This could be improved.

The authors would like to thank the reviewer for the positive, constructive and thorough review. All of the major/minor comments have been address below. Along with comments from reviewer #1, they significantly improved the quality of the manuscript. In particular, the methodology section has been improved to provide more details on the radiative transfer model used and its parameterization as well as the details on the SVM model used to classify grain type.

2 Major comments

Section 3.2 is the main problem of the paper, and the only reason why I suggest a major revision. Many key details are missing, and the text in the section does not fully describe the model setting. E.g., which of the multitude of SMRT scattering models was used? How many layers were used in the simulation? How were other parameters than the retrieved ones defined for these layers (e.g. snow depth and density)? One has to read between the lines or reach out all the way to the end of the discussion to get some answers. For example, line 208 refers to "the multi-layer analysis", but it is not clear how many layers there are (two, three, or more?). This only becomes clear (perhaps) only later in the manuscript, that two layers were used. As a further example, the last sentence states that "The different effective parameters were thus constrained by values found in the literature", without giving the values. Please modify the entire section and explain fully 1) the model setup, including which scattering model was used in SMRT 2) state carefully all model parameters and from what source these were derived from (measured, retrieved, literature etc). Maybe a Table could help? E.g. at present it is not fully traceable how all the measurements described in Section 2.3 were finally used in simulations, validation or both.

This section has been revised with more details on the SMRT setup, the multi-layer (which corresponds to the results of Figure 13) and two-layer approach taken and which dataset (MagnaProbe, SMP, snowpit, soil) was used as input to SMRT.

In this study, the Snow Microwave Radiative Transfer (SMRT, Picard et al., 2018) model was used to simulate the backscattered signal (σ^0) at C-, X-, and Ku-Band at VV polarization. SMRT is a multi-layered snow radiative transfer model where each layer is characterize by, minimally, its thickness, density, temperature, grain size (SSA, optical diameter or correlation length) and the model used to represent its microstructure. The calibrated SMP profiles provided thickness, correlation length and density and the temperature was inferred from the snowpit measurements. With these inputs, the microwave properties such as, interface reflectivity, volume scattering, absorption are computed using the desired physical models, frequency and incidence angle. Finally, it solves the radiative transfer equation, to calculate the surface backscatter, in the case of active microwave sensors, using the Discrete Ordinate Radiative Transfer (DORT, Picard et al., 2004, 2013). Of the inputs, to properly simulate σ^0, the following parameters need to be accurately estimated: 1. the background roughness and permittivity (Meloche et al., 2021; Montpetit et al., 2018) and 2. the snow microwave grain size (Picard et al., 2022) related to microstructure and volume scattering. In this study, the Improved Born Approximation (IBA, Mätzler, 1998) was used for the volume scattering component with an exponential auto-correlation model to represent the snow microstructure, similarly to King et al. (2018); Montpetit et al. (2013). [...]

The number of layers were determined by the SMP profile processing described in section 2.3. The SMP profile selection was based on using the SMP profile with the snow depth that best corresponded to the median snow depth of all MagnaProbe measurements for a given site. For discussion purposes, and in the objective of improving computational efficiency, further testing using a two-layer snowpack was performed, where the median values of the rounded and depth hoar grain type layers, using all the measured data, including MagnaProbe, SMP profiles, and snowpits, was used to determine their snow geophysical properties (e.g., thickness, temperature, SSA, density).

The section could also benefit from a (brief) introduction of the SMRT and the GO models. Just a sentence or two placing the models in context for a potential reader who has no idea what these models actually do, could be sufficient. e.g. “SMRT (Picard et al., 2018) simulates propagation of microwaves in snow, generating estimates of microwave emission and backscatter from a stacked system of snow layers, with each layer described by…” and so on.

The two models are now introduced in section (see previous comment for SMRT):
The GO model is a high frequency approximation of the analytical Kirchhoff solutions, which describes the surface scattering of a very rough surface with no coherent scattering component.

A similar short intro should be added on snow microstructure, in particular the relatively new concept of microwave grain size introduced by Picard et al., how this is obtained from field measurements, and where Polydispersity comes in. Maybe this warrants a separate subsection in Methods?

We feel an entire subsection on polydispersity is not needed because it would repeat what is described in depth in Picard et al. (2022). Instead, we have added a few lines on polydispersity to Section 3.3:
In this study, polydispersity is simply retrieved, but such a parameter can be measured in the lab from micro-tomography measurements (Picard et al., 2022). This parameter describes the "non-uniformity" of the snow microstructure length scales in all directions. To describe the microwave snow grain size, polydispersity is a multiplying factor to the snow correlation length which can be estimated from SMP measurements.

3 Minor comments

The title is a bit awkward to me. “Retrieval of airborne Ku-band SAR…” does not really say anything (retrieval of what? radar backscatter?). Please consider changing the title to e.g. “Retrieval of snow and ground properties from airborne Ku-band SAR…”, or even “Retrieval of snow polydispersity and ground effective permittivity from Ku-band SAR…” since those are the parameters you finally retrieve.

Good point. The title was changed to:
Retrieval of snow and soil properties for forward radiative transfer modeling of airborne Ku-Band SAR to estimate snow water equivalent: The Trail Valley Creek 2018/19 Snow Experiment

Abstract line 4. Not sure about “quality snow information”. I would change this to something less ambiguous, e.g. simply “snow information”

Has been changed to *accurate snow information* since the objective is to indicate that these measurements don’t simply provide snow information but information of a certain "value".

Abstract line 6. “It becomes possible to properly characterize” is also quite a strong statement. What is properly? I’d suggest something like “(SMP and SMRT)... are promising tools for characterizing the snow cover ... etc”

Text has been changed to:

Recently developed tools like the Snow MicroPenetrometer (SMP), to retrieve snow microstructure data in the field, and radiative transfer models like the Snow Microwave Radiative Transfer Model (SMRT), are promising tools for characterizing snow and how it translate into radar backscatter.

Abstract line 15. Polydispersity is a very new concept in snow microwave modeling and you should give some short context for the term. e.g. “The polydispersity of the snow microstructure, which together with snow autocorrelation length has been proposed as a basis for scattering calculations of microwaves propagating in snow,...” (please use some wording better fitting your text). See also later comment on adding a paragraph, or even a separate section, on the concept of microwave grain size.

Text has been modified to:

Recently, it was shown that snow grain size, represented by exponential correlation length, could be translated to its equivalent "snow microwave grain size" by a parameter called polydispersity. Values of 0.74 and 1.11 for rounded and depth hoar snow grains polydispersity, respectively, was retrieved.

Abstract, last sentence. Since you have not demonstrated actual SWE retrieval in this study, I suggest to modify this a bit: “... using a priori knowledge of the snow conditions to simulate backscattering, facilitating also the possible retrieval of SWE from these measurements” (or similar).

Text has been changed to:

[...] , which is of great importance in SWE retrieval algorithms from Ku-Band SAR measurements.

Introduction line 38-39: “decomposing...” I’d rather say the overall problem in SWE retrieval is separating the influence of both variable microstructure and ground backscatter on total backscatter (as opposed to separating these from one another, maybe just change “from” to “and”?). Also change “ground permittivity” to “ground backscatter”. I also suggest to change the wording so that you acknowledge these vary also spatially, not only temporally.

Text has been modified to include suggestions:

Advancement of a Ku-band radar-based SWE retrieval is highly dependent on decoupling the strong spatial and seasonal influences of snow microstructure and background backscatter (Picard et al., 2022; Meloche et al., 2021).

Intro line 68. “Is most sensitive to SWE when a priori snow microstructure is known” does not really make sense. The sensitivity to SWE remains the same (weak or strong) whether or not we know what the microstructure is. I guess you mean “the sensitivity to SWE can be predicted when a priori snow microstructure is known”, or similar. Please reword.

Reworded:

These studies (e.g., Tsang et al., 2022; Lemmetyinen et al., 2022; King et al., 2018) have shown that the Ku-Band frequency range is most sensitive to SWE, and a priori knowledge of snow microstructure is necessary to accurately estimate SWE.

Section 2.1 line 117 "prevents good forward modeling" is a bit inaccurate, since you could simulate also wet snow effects with e.g. SMRT, which would be just as "good". Rather, the problem is that meaningful retrievals of SWE, microstructure or ground properties become difficult due to the overwhelming influence of wet snow on the radar signal? Please reword.

Reworded:

Some liquid water content in the top portion of the snowpack was also present which reduces the influence of ground properties and snow microstructure in forward modelling of the snowpack due to the overwhelming influence of wet snow on the radar signal.

section 2.2 lines 128-131. The sentence is a bit awkward to me. Maybe split into two sentences after "were considered"?

Sentence was split and second sentence was reworded to:

[...] . Only imagery that showed intensity variability (standard deviation) below 2 dB, from one image to another, for all surveyed sites, were considered.

section 2.3 lines 142: you state that "it was possible to determine the freeze-thaw state of the soil and provide modelling inputs to estimate the background scattering". However, to what I see, these measurements were finally not used, but all ground values were retrieved ones? Did you try comparing retrievals to measured permittivities? If not, it is not necessary to report these measurements.

The permittivity and roughness were only retrieved yes. The retrieved permittivities were not compared with the measured ones since they were not measured for the same frequency range. Nonetheless, they were used to ensure that the soil state was constant in the 2-weeks buffer period used for satellite imagery selection. The soil temperature was used as a model input for the static sites, though it had little influence on the soil backscatter since the permittivity was retrieved. The dataset is kept in the manuscript since it is linked to the rest of the campaign and the dataset is published with the rest. The text was modified to clarify:

The soil sensor networks collected hourly measurements of temperature, moisture, and complex permittivity, in the MHz range, during the experiment. From these measurements it was possible to determine the freeze-thaw state of the soil, which was used for satellite imagery selection, and provide soil temperature measurements as modelling inputs to estimate the background scattering for the static sites.

Section 4.1 line 240. The values stated in the text seem to contradict Figure 4 and Table 3, please verify.

Modified:

[...] mainly concentrated around 0.5 during November and increases to 0.7 throughout the winter.

Line 259 typo, remove (Calonne2000)

Removed

Section 4.4 line 307. Permittivity parameter? Do you mean soil permittivity?

Yes, it was changed in the text:

As shown in Section 4.3, the soil permittivity in the GO surface scattering model is frequency dependent.

lines 311-312. Here you introduce a previous scaling factor, but no explanation is given why this should be comparable to polydispersity. One has to dig into the paper by Picard et al. for clues, but it should be explained it here. See previous comment on adding short introduction/explanation of the microwave grain size concept.

The concept is now introduced in the methods section. Text was modified here as well:

The scaling factor $\phi = 1.09$*, which is comparable to polydispersity (see section 4.4), [...]*

Figure captions in general, here Figure 6 as an example: The captions should enable the reader to understand the figure without referring to the text. Instead of a generic "Results of calibrated SMP snow density measurements", explain the two panels in the figure (scatterplot and histogram) fully in the caption, including information on what was used in the calibration (i.e. snow pit profiles). Please check that captions of all figures and Tables provide sufficient information.

Captions have been modified to be self sufficient.

line 281 typo: Grandell

Great catch, the downloaded bibtex file from Scopus.com was wrong. New file from IEEE was used to generate the proper citation/reference to (Pulliainen et al., 1999)

Discussion: did you compare retrieved soil permittivity values at all to measurements? What does literature and models say about the frequency dependence of permittivity of frozen ground (largely controlled by permittivity of ice)? At least the latter should be discussed, even though the retrievals represent "effective" values. If a comparison to the measured ground permittivities did not yield anything conclusive, this could also be at least mentioned.

A comparison with measured soil permittivities was not conducted since the measurements were made in the MHz range and cannot be compared with retrieved permittivities in the GHz range. Text was added to discuss the frequency dependence of frozen ground permittivity:

Results of tables 6 and 7 show and increase of the soil permittivity with frequency. This goes against the modelled frequency *dependency of soil permittivity (Mironov et al., 2017; Zhang et al., 2010), which highly depends on the permittivity of ice and the ice-fraction in the soil. Montpetit et al. (2018) reported the same frequency dependency as shown here, from retrieved permittivity values using passive microwave radiometer data, and a different reflectivity model for similar soil types. This tends to indicate that retrieved values from microwave measurements (both active and passive) are sensitive to different components of the soil vertical profile, where models describe the frequency dependence of homogeneous soil samples.*

Discussion, lines 400-403. One has to read all the way here to understand the simulation setup. Please move this explanation to Methods, adding other necessary details (see previous comments)

Some of this information was included in section 3.3 but the following text, in section 3.3 was modified to improve the simulation setup description. This is in addition to the description of the SMRT model and its functionalities used in this study. *For every optimization process at every site of the January 2019 campaign, the most representative SMP profile was selected to provide input of snow properties to SMRT for the multi-layered snowpack analysis. The number of layers were determined by the SMP profile processing described in section 2.3. The SMP profile selection was based on using the SMP profile with the snow depth that best corresponded to the median snow depth of all MagnaProbe measurements for a given site. For discussion purposes, and in the objective of improving computation efficiency, further testing using a two-layer snowpack was performed, where the median values of the rounded and depth hoar grain type layers, using all the measured data, including MagnaProbe, SMP profiles, and snowpits, was used to determine their snow geophysical properties (e.g., thickness, temperature, SSA, density).*

Conclusions, lines 418-419. Increased and decreased compared to what? I am assuming the ranges introduced by Picard et al., but this should be made clear. Also, note that Picard et al presented the first estimates of these parameters, so finding values outside of these ranges is not surprising.

Reworded:

[...] we showed that the snow volume scattering was dominated by the depth hoar layer, where K_{H} increased the grain size, thus its volume scattering (~ 1.11), and the K_{R} of the rounded grain layer reduced it ($\sim$ 0.74).

line 430 “background properties should be similar. . . ” I do not follow. Why should these be similar?

Reworded with regards to the conclusions of Zhu (2021) who stated that the soil backscatter should saturate in the Ku-K-Band range.

The lower Ku frequency is more sensitive to the soil backscatter contribution than the higher Ku frequency, due to the higher sensitivity to snow volume scattering at the higher frequency. The fact that the background properties should be similar for both frequencies, due to the saturation of the permittivity in the Ku range (Zhu, 2021), would allow isolation of the background surface scattering component from the snow volume scattering component of the signal received by a dual-frequency sensor.

line 442: “. . . skillful forward modelling of the radar signal in the tundra region”.

Modified.

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