

The Cryosphere Discuss., author comment AC2
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Reply on RC1

Julie Z. Miller et al.

Author comment on "An empirical algorithm to map perennial firn aquifers and ice slabs within the Greenland Ice Sheet using satellite L-band microwave radiometry" by Julie Z. Miller et al., The Cryosphere Discuss., <https://doi.org/10.5194/tc-2021-116-AC2>, 2021

Author Response to Reviewer #1

The paper comprehensively describes the method for analysis and the modeling exercise. The authors present the results and fairly point out the sources of uncertainty. I find this paper a valuable contribution to our knowledge of using L-band radiometry for mapping of subsurface features of the GrIS. Nevertheless, I believe the paper could be much more concise. Thus, in addition to addressing the scientific comments and questions, I strongly suggest that authors try to shorten the text which I hope leads to fewer redundancies and better readability.

Note: the editor asked the authors to respond to the reviewers' comments before revising the paper. So, the authors have described the intended revisions.

The authors thank Reviewer #1 for the positive response and detailed review of a long manuscript. We will significantly shorten the manuscript and will remove the redundancies to improve the readability. We have provided detailed responses to the insightful technical questions.

General Comments and Technical Questions

(1) L 509: The closer we are to the Brewster angle, the less sensitive the TBV measurements are to the snowpack dielectric properties. In other words, TBV observations are more sensitive to the subnivean layer properties. With this in mind and that the SMAP observations are at 40°, could you describe the uncertainties introduced to your analysis when considering an ice surface temperature of -1°C and linking them to the TBV measurements?

Great question!

The authors struggled with this uncertainty while developing the original algorithm (Miller et al., 2020), and then made the decision not to use the MODIS ice surface temperature measurements in the adapted algorithm (this paper), although they are shown in Figure 4. Frequency differencing to look for surface and subsurface meltwater is a good theoretical concept, however, it is not ideal when applied to satellite data. The 'uncertainty gap' between the lack of sensitivity to the dielectric changes at the Brewster angle (i.e. surface melting) in the SMAP TB data and assuming melt when the MODIS ice surface

temperature has potentially not actually reached the melting point (i.e., -1°C) was easily observed when partitioning L-band TB time series. MODIS ice surface temperature measurements are also significantly influenced by the presence of clouds. There were often significant surface melting events in the SMAP TB data after surface freeze-up as detected by the MODIS ice surface temperature measurements. The poorly partitioned L-band time series that sometimes included sharp increases were then fit to the sigmoidal curves, which led to uncertainty in the mapping. Changes in the curve fitting values (i.e., rate of TB decrease) could change the mapped boundaries by hundreds of square kilometers.

The authors alternatively used maximum and minimum SMAP TB values to partition L-band TB time series.

From the paper (L813-819)

The key advantage of this approach is that maps can be generated using TB imagery collected from a single satellite, which simplifies the adapted algorithm. Another advantage is that unlike TB collected at shorter-wavelength thermal infrared frequencies (e.g., MODIS), TB collected at longer wavelength microwave frequencies (e.g., SMAP) are not sensitive to clouds, which eliminates observational gaps and cloud contamination, and provides more accurate time series partitioning and more robust curve fitting.

(2) Can you explain more what do you expect to be the effect of using multi-angle TB measurements on your analysis results?

Multi-angle L-band TB measurements (e.g., SMOS) introduce a tool to help differentiate how volume and surface scattering components contribute to the observed TB at the surface of the ice sheet, and how this contribution changes with time. For L-band emissions in the percolation facies, the dominant control on volume scattering is embedded ice structures (i.e., ice pipes and lenses), and the dominant control on surface scattering is the volumetric fraction of meltwater within the water-saturated layer, or possibly the surface roughness of the solid-ice layer (i.e., ice slab). Analysis of multi-angle TB measurements may provide an increased understanding about refreezing processes at depth within the water-saturated firn layer. For example, if a water-saturated firn layer refreezes as an ice slab, the surface scattering component may dominate. However, if a deep perennial firn aquifer exists at depth, volume scattering from the embedded ice pipes and lenses in the overlaying firn may dominate.

(3) The authors have used enhanced-resolution L-band imagery which includes using multiple satellite overpasses over an area for improving spatial resolution. Given the fact that surface melt could be significantly different between two local overpasses at the similar local times but different days, would you expect to see a difference if you'd repeat your work with the original lower resolution SMAP data?

Surface melting events over perennial firn aquifer and ice slab areas typically saturate deeper firn layers with meltwater relatively quickly (i.e., ~days-weeks), and deeper firn layers typically remain water-saturated throughout the melting season (i.e., ~months). This results in a superimposed signal – where the rapid daily temperature cycling signal is superimposed over the slowly-varying seasonal signal from the deeper water saturated firn layers (e.g., Figs. 1 & 2). Our algorithm detects the slowly varying seasonal signal from the deeper water saturated firn layers. The maps generated using the enhanced resolution TB data will have a higher effective resolution gridding as compared to the coarse-resolution TB data, which will refine the boundaries of the area mapped. This is the key difference we've observed when applying the algorithm to the different TB data sets.

(4) In the last section, when talking about future work and potential ideas to follow, it is perhaps good to shed light on the usefulness of other satellites' data or future missions.

As an example, ESA's ROSE-L mission could provide us with valuable lower frequency active measurements of the ice sheets.

The authors will add a short discussion on the potential advantages of using an active microwave sensor (e.g., ROSE-L or NISAR) or a combined active/passive technique (e.g., SMAP, SMOS, CIMR, Cryorad). The advantage of active microwave sensors is the improvement in spatial resolution. An advantage a combined active-passive microwave technique is the differing sensitivity to physical temperature.

More detailed comments:

L 40—44: The sentence is too long. Please break it down to two or three sentences for improved readability. "An empirical algorithm previously developed to map the extent of Greenland's perennial firn aquifers via fitting exponentially decreasing temporal L-band signatures to a set of sigmoidal curves is recalibrated to also map the extent of ice slab and perched firn aquifer areas using airborne ice-penetrating radar surveys collected by NASA's Operation Ice Bridge (OIB) campaigns (2010-2017)." □ ""An empirical algorithm was previously developed to map the extent of Greenland's perennial firn aquifers via fitting exponentially decreasing temporal L-band signatures to a set of sigmoidal curves. This algorithm is recalibrated to also map the extent of ice slab and perched firn aquifer areas using airborne ice-penetrating radar surveys collected by NASA's Operation Ice Bridge (OIB) campaigns (2010-2017)."

Thank you. Sentence wording will be changed in the text to your suggestion.

L 59: "~tens" □ "approximately tens"

This change will be made.

L 110—144: It is just a suggestion. Can the authors include a table that help summarize and explain the formation features and relative TBs of each of the three types of firn structures they discuss in the introduction? For example the rows could be "percolation facies areas", "ice slabs", "perennial firn aquifer areas". The introductory material is written well; nevertheless, it is a bit long for an introduction section in a paper.

The authors careful considered this suggestion – as it is a good one. However, a similar table with values derived from the analysis is already included in the Methods section (Table 2). The authors will significantly shorten the introduction.

L 175—197: This part can be shortened as it goes into details which best fit in the "Methods" section.

L 272-277: The statement given in these lines is basically the same as in lines 175 to 183. Please remove these redundancies.

L 175-197, and L 272-277 will be combined and significantly shortened in a paragraph at the beginning of the methods section - which will address the previous two comments.

L 209—214: I see this as a redundancy to the same information provided in the "Introduction" section.

L 218: "since the beginning of the satellite era" unnecessary. Can be omitted.

L 233—234: "Deep enough to directly detect the upper surface of stored meltwater over the entire depth range mapped by airborne ice-penetrating radar surveys over the GrIS." This sentence is grammatically incorrect. Please revise it.

L 236: The beginning of Section 2.2 contains introductory information about SMAP. It is best to include such information in Section 2.1. where you first talk about SMAP and using its passive observations.

Section 2.1 will be removed to shorten the manuscript – which addresses the previous four comments.

L 323: "Enhanced-resolution (3.125 km)". This expression potentially created a misunderstanding in reader's mind. The grid is 3.125 km while the actual spatial resolution is at best ~18 m. Please revise the wording to avoid this misunderstanding. The same comment is true for the caption of Fig. 1.

The authors agree that it is important to note the difference between the gridding and the effective resolution. The wording in Fig. 1 and Fig. 2 will be changed to:

Conventionally processed (25 km gridding, ~30 km effective resolution)
Enhanced-resolution (3.125 km gridding, ~18 km effective resolution)

L 326: "(Brodzik et al., 2019) "This reference does not seem to be needed here.

Brodzik et al., 2019 is an enhanced resolution data citation for the figures, which is required by the The Cryosphere. For clarity, the reference will be changed changed in both Fig. 1 and Fig. 2 to:

L-band TVB imagery (Brodzik et al., 2019)

L 327: There is no panel (c) in Fig.2. It seems that the statement for panel (c) is copied and pasted in the caption for Fig 2.

General comment about figures and their captions: The figure captions are too long and they seem to go beyond a general description necessary to read the maps over to detailed discussion of the content.

The figure captions will be significantly shortened, and the more descriptive text will be removed.

Figure 3: Please explicitly write the unit of the values in the colorbars next to the radargram profiles (panels (a) and (b)).

This will be corrected. The colorbar/units were clipped off by mistake.

L 450: Much of the text after Table 2 can be summarized. Thanks to Table 2, there is not a strong need of writing down the same numbers within the text.

Good observation! Text will be revised and shortened.

L 459 – 469: At this point we are far away from the "Introduction" and you include unnecessary background information including about the methods for mapping Greenland's ice facies. Please remove these statements and simply explain the method you have developed for this purpose based on L-band measurements.

Section 2.4.1 (and these lines) will be removed to shorten the manuscript.

L 1130–1133: Please keep the Summary and Future Work section free from material which are supposed to be in the "Introduction".

These lines will be removed.