Author Response to Reviewer #1 (Author responses are highlighted in orange)

This manuscript introduces a highly relevant and impactful application of L-band radiometry in a relatively unexplored research field. The manuscript is generally of very high quality, well written, and with excellent figures. I recommend a few clarifications and comments below. I look forward to seeing the progress on this manuscript and the further development of this method (data product?) in the future.

The authors would like to thank the reviewer for the prompt and comprehensive review and thoughtful comments.

1. At the end of the introduction, you mention and cite a few previous attempts using passive microwave to quantify liquid water on the ice sheet. Can you briefly summarize the work to date and mention how the content of the manuscript adds to or differs from the current status of the subject?

In my opinion one of the primary novelties of the manuscript is the demonstration of liquid water retrieval with single-angle L-band satellite observations. You might also want to consider citing the below paper which also demonstrated single-incidence angle retrievals of snow liquid water but using a ground-based radiometer. *Naderpour, R., Houtz, D., & Schwank, M. (2021). Snow wetness retrieved from close-range L-band radiometry in the western Greenland ablation zone. Journal of Glaciology, 67(261), 27-38.*

We will revise the relevant section in the introduction to include the literature review given above, as follows:

Houtz et al. (2019) used the Soil Moisture and Ocean Salinity (SMOS) multi-angle L-band radiometric observations with a two-layer configuration of the L-band specific MEMLS (LS-MEMLS) model in an inversion-based retrieval framework for simultaneous estimation of snow liquid water content and density at the Swiss Camp site located in the ablation zone of the western Greenland ice sheet (GrIS). This initial study evaluated the results with in situ air temperature and another satellite-based empirical melt detection algorithm (the cross-polarized gradient ratio of 19 GHz and 37 GHz TBs); however, it did not include any in situ validation of actual liquid water amount. Naderpour et al. (2021) supported Houtz et al. (2019) finding using a close-range (CR) single-angle L-band microwave radiometer measurements and the same L-band specific forward model (LS-MELMS) at the Swiss Camp. Houtz et al. (2021) extended the Houtz et al. (2019) approach to the entire GrIS. They tuned the wet layer thickness (10 cm – 100 cm) to provide variable estimates of liquid water which also were not validated against any reliable reference. Field observations and modeling results provide evidence of meltwater infiltration for more than 100 cm, especially in the percolation zone of the GrIS (e.g., Samimi et al. 2021; Vandecrux et al., 2020). Mousavi et al. (2021) developed an L-band specific snow/firn radiative transfer model to derive multidimensional brightness temperature look up tables for the frozen and melt season considering a four-layer ice sheet structure. The algorithm uses frozen season brightness temperature to determine the baseline emissions (temperature, density, scattering coefficient) which are then used in melt season to estimate liquid water content and corresponding wet layer thickness. In this manuscript, we extend Mousavi et al., (2021) approach with improved and updated LUT to quantify and validate the LWA with two state-of-the-art surface energy balance models forced with in situ observations and reanalysis data products.

2. In equation (1) isn't this neglecting reflection?

Yes, Eq. 1 is a simple Rayleigh-Jeans approximation ignoring internal reflections and scattering, it is mentioned in lines 110-111 that "if firn were vertically homogeneous or isothermal", the TB could be found by this simple relation. But firn is neither isothermal nor homogeneous. So, TB are described by multi-layer radiative transfer (RT) equations (e.g., Eq. 2), which consider the depth-integrated product of physical temperature and emissivity, considering the emissive, absorptive, and scattering properties of the snow, firn, or ice layers. Eq. 1 was given as an introduction for general readers to clarify what radiometers measure and what the brightness temperature represents. But as the background discussion proceeds, actual snow/firn emission and radiative transfer with the emissive, absorptive, and scattering properties is clarified (lines 113-150).

3. Can you clarify in the RT model if multiple scattering or coherence are being considered or not? I see now in line 216 "incoherent approach", can you quickly qualitatively explain this assumption?

The RT model is incoherent and considering larger wavelength of L-band emissions (21 cm), we assume that this assumption does not pose a major issue. The model also does not calculate multiple scattering analytically. However, to account for the combined reflective effects by the complex stratigraphy due to numerous ice layers common in the percolation zone of the GrIS, as well as the effects of multiple scattering in the snow/firn layer, we consider a hypothetical highly reflective layer (Layer 2 underneath the dry/wet snow layer) by explicitly specifying its dielectric constant (with high real part that varies spatially).

4. Line 207, is there any justification to choosing the frozen and melt season reference dates? These would also vary with latitude and elevation.

There is no consensus in reference dates, however, Jan 1 – Mar 31 is generally considered fully frozen conditions regardless of elevation and latitudes. However, SMAP does not have data for Jan 1 – Mar 30, 2015, because the data production started on March 31, 2015; therefore, we extended the reference period to Apr 7th for all the years to make it consistent. October 24 – December 31 was determined based on visual observations of the time series during 2015-2023. We will add these clarifications in the revised manuscript.

5. I don't quite understand in line 215 how the top layer is considered infinite thickness and then discrete thickness layers are used beneath this? Maybe this just means that no attenuation is considered in these layers, only refraction, so it is independent of layer thickness?

The top layer is simply air above the snow and assumed to be semi-infinite (surface to radiometer antenna, top of the atmosphere at an altitude 685-km SMAP orbit).

6. In line 248, How is 5% determined to be the maximum volume fraction of water? What about large supraglacial lakes?

Experiments performed by Colbeck, (1974) suggest that because of capillary retention, the irreducible water saturation of dense snow/firn is 7% of its pore volume. Coléou and Lesaffre, (1998) showed that the irreducible water content can be up to 6.5 - 8.5 % of the pore volume depending on the density. Based on these studies, and considering snow/firn density in the percolation zone, we determined the maximum volume fraction to be 5%. Furthermore, we performed histogram analysis of model estimated liquid water content (Samimi et al., 2021 EBM model with in situ data) in the percolation zone to determine the maximum liquid water content. We found the range of volume fraction of liquid water is within 5%.

The focus of the manuscript is the percolation zone of Greenland ice sheet which does not include areas of large supraglacial lakes. However, we discussed the L-band radiometric responses of ablation zone where supraglacial lakes are located. Our detection algorithm can detect the presence of meltwater in the ablation zone, but it was not possible to quantify the amount of liquid water in these areas with the current algorithm. So, we masked the melt detection in these areas (Fig. 8). Supraglacial lakes and other intricate features in the ablation zone pose challenges for radiometric liquid water estimation. Due to soaked snow, the brightness temperature quickly saturates and decreases during melt season. We included discussion on this in lines 501-509 as a path forward.

7. Line 260. Can you explain "the inversion only considered increasing TBs for LWA quantification". How is "increasing" versus "decreasing" determined? From one daily average to the next? Does this assume that melt always increases brightness temperatures?

The increasing and decreasing are determined with respect to the frozen season reference threshold (T) as determined by Eq. 2 (i.e., mean frozen season TB plus/minus 10 times STD). Fig. 2 illustrates the areas where the TB increases (percolation zone) and decreases (ablation and higher accumulation zone) in the melt season due to melt. As shown, melt can both increase and decrease TB depending on the area (or amount of melt). Our detection algorithm considers both increasing and decreasing TBs during melt season to detect melt (any TB beyond threshold, higher or lower, is considered as melt. See the sample detection in Fig. 2 indicated by blue square symbols). However, our LWC quantification algorithm only considers the increasing case in the percolation zone.

What about the reflective effect after water volume fraction becomes high and TB decreases again?

In the percolation zone, the assumption is that the LWC is constrained to the maximum volume fraction (5%), preventing the reflecting effects becoming dominant.

8. Line 363, "The AWS measurements that run the model" maybe "The AWS measurements for which the model was run" or "The AWS measurements that are the driving inputs of the model".

It will be revised as suggested.

9. Line 416 "2025 – 2023" I think you mean 2021-2023?

Yes, we meant 2021 – 2023. Sorry, it was a typo, and it will be corrected in the revised manuscript.

10. Line 498 mentions firn aquifers. What is the current status of identifying these? Will they be unidentifiable in the product because the frozen versus melt season TBs do not vary much? Are they apparent in the magnitude of the frozen season TBs? I believe this has been addressed to some degree in the literature, it might be helpful to add some references.

As we discussed in the lines 496-500, the detection algorithm follows a threshold-based technique that uses winter reference of the TB to detect melt events, while perennial firn aquifers store a large quantity of the LWA throughout the year. Miller et al. (2020, 2022b, a, 2023) represent the current status of identifying them.

The signal used to identify the aquifers during the frozen season in the Miller et al. studies is an order of magnitude smaller than what the melt signal is. Therefore, the firn aquifers do not affect the detection and quantification of the meltwater amounts.

We cited firn aquifer detection and modelling studies and will review the literature again to makes sure all relevant studies are included.

11. In addition to the technical limitations mentioned in the conclusion, I believe it could show great impact to also discuss longer-term plans and potential of this dataset. E.g. Is there any plan to provide integrated melt-water estimates across the ice sheet or use these retrievals in a bigger picture Surface Mass Balance study? Is there a path or plan towards generating a SMAP data product based on this algorithm?

We agree to and appreciate the reviewer's perspective that we may discuss more about our longer-term plans and potential of this dataset. The initial results included in the manuscript demonstrate SMAP's capability to measure both surface and subsurface meltwater across the percolation zone of the Greenland ice sheet, offering deeper insights into sub-surface conditions. Our long-term goal is to create a liquid water amount data product across GrIS, which can be used in GrIS surface mass balance study, including process level problems such as meltwater generation, retention (refreezing), and runoff, ice sheet and glacier surface evolution, atmospheric feedback etc. It can also be used to better constrain and validate regional climate models.

To provide a longer time data product, we are currently working to integrate SMOS observations (2010 - present) with SMAP. A detailed sensitivity analysis and uncertainty characterization of the LWA retrieval algorithm, including dielectric mixing models is underway. We are also investigating the added benefits of other complementary frequencies (6 GHz up to 36 GHz bands), aiming at CIMR (ESA's Copernicus Imaging Microwave Radiometer to be launched in 2029) which will include coincident L (1.4 GHz) - Ka (36 GHz) channels (Colliander et al., 2024; Kilic et al., 2018), for the first time, to provide a possible depth profile of the LWC. The algorithm can also be extended for LWA estimation in Antarctic Ice Sheet.

At the moment the SMAP mission has not decided to generate an operational meltwater product but that may change in the future.

A brief discussion on these future research directions will be added in the conclusion of the revised manuscript.

References:

Colbeck, S. C.: The capillary effects on water percolation in homogeneous snow, J. Glaciol., 13, 85–97, https://doi.org/10.3189/s002214300002339x, 1974.

Coléou, C. and Lesaffre, B.: Irreducible water saturation in snow: experimental results in a cold laboratory, Ann. Glaciol., 26, 64–68, https://doi.org/10.3189/1998aog26-1-64-68, 1998.

Colliander, A., Hossan, A., Harper, J., Vandecrux, B., Miller, J., Marshall, S., and Donlon, C.: Towards Ice Sheet and Ice Shelf Meltwater Profile Retrieval from Copernicus Imaging Microwave Radiometer (CIMR), 4–5, 2024.

Houtz, D., Naderpour, R., Schwank, M., and Steffen, K.: Snow wetness and density retrieved from L-band satellite radiometer observations over a site in the West Greenland ablation zone, Remote Sens. Environ., 235, 111361, https://doi.org/10.1016/j.rse.2019.111361, 2019.

Houtz, D., Mätzler, C., Naderpour, R., Schwank, M., and Steffen, K.: Quantifying Surface Melt and Liquid Water on the Greenland Ice Sheet using L-band Radiometry, Remote Sens. Environ., 256, https://doi.org/10.1016/j.rse.2021.112341, 2021.

Kilic, L., Prigent, C., Aires, F., Boutin, J., Heygster, G., Tonboe, R. T., Roquet, H., Jimenez, C., and Donlon, C.: Expected Performances of the Copernicus Imaging Microwave Radiometer (CIMR) for an All-Weather and High Spatial Resolution Estimation of Ocean and Sea Ice Parameters, J. Geophys. Res. Ocean., 123, 7564–7580, https://doi.org/10.1029/2018JC014408, 2018.

Miller, J. Z., Long, D. G., Jezek, K. C., Johnson, J. T., Brodzik, M. J., Shuman, C. A., Koenig, L. S., and Scambos, T. A.: Brief communication: Mapping Greenland's perennial firn aquifers using enhanced-resolution L-band brightness temperature image time series, Cryosphere, 14, 2809–2817, https://doi.org/10.5194/tc-14-2809-2020, 2020.

Miller, J. Z., Culberg, R., Long, D. G., Shuman, C. A., Schroeder, D. M., and Brodzik, M. J.: An empirical algorithm to map perennial firn aquifers and ice slabs within the Greenland Ice Sheet using satellite L-band microwave radiometry, Cryosphere, 16, 103–125, https://doi.org/10.5194/tc-16-103-2022, 2022a.

Miller, J. Z., Long, D. G., Shuman, C. A., Culberg, R., Hardman, M., and Brodzik, M. J.: Mapping Firn Saturation Over Greenland Using NASA's Soil Moisture Active Passive Satellite, IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., 15, 3714–3729, https://doi.org/10.1109/JSTARS.2022.3154968, 2022b.

Miller, J. Z., Long, D. G., Shuman, C. A., and Scambos, T. A.: Satellite Mapping of the Extent and Physical Characteristics of an Expansive Perennial Firn Aquifer in the Wilkins Ice Shelf, Antarctic Peninsula, 219–222, https://doi.org/10.1109/igarss52108.2023.10281647, 2023.

Mousavi, M., Colliander, A., Miller, J. Z., Entekhabi, D., Johnson, J. T., Shuman, C. A., Kimball, J. S., and Courville, Z. R.: Evaluation of Surface Melt on the Greenland Ice Sheet Using SMAP L-Band Microwave Radiometry, IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., 14, 11439–11449, https://doi.org/10.1109/JSTARS.2021.3124229, 2021.

Naderpour, R., Houtz, D., and Schwank, M.: Snow wetness retrieved from close-range L-band radiometry in the western Greenland ablation zone, J. Glaciol., 67, 27–38, https://doi.org/10.1017/jog.2020.79, 2021.