Authors Response to:

Review of Mapping Greenland's perennial firn aquifers using enhanced resolution L-band brightness temperature image time series

Thank you for your thoughtful comments!

Specific Comments L66: This newly published paper could be of interest here as it uses Sentinel-1 to map firn aquifers from space: Brangers, I., Lievens, H., Miège, C., Demuzere, M., Brucker, L., & De Lannoy, G. J. M. (2020). Sentinel-1 detects firn aquifers in the Greenland ice sheet. Geophysical Research Letters, 47, e2019GL085192. https://doi.org/10.1029/2019GL085192.

Added citations. See L60 and L319.

L90: It would be helpful if you could state here what the resolution needed to map firn aquifers is and in how many passes this can typically be achieved

Not enough is known about perennial firn aquifers to answer the question of resolution. The airborne observations are far too sparse, and leave many unanswered questions about the behavior of firn aquifers in the boundary regions and between flight lines.

L-band is the only frequency with a penetration depth capable of directly observing the upper surface of meltwater throughout the winter. However the resolution is relatively coarse (as compared to say, a SAR) and the record only starts recently (SMOS, 2009). Given the shallow penetration depth (~several meters) C-band can only observe meltwater for a few months, at most, after surface melting ends and thus an inference is made which leaves uncertainty the ultimate fate of meltwater (perennial?) in the mapping. However, there is a record that dates back to ~1992 (AMI, ERS satellite series). Mapping is really dependent on the availability of satellite data, rather than a specific resolution.

L233: I would say in steps of 0.004 rather than in time steps of 0.004 which is confusing as you increase the exponential rate and not the time parameter

Revised in text. See L233-234

incremented by steps of 0.004

L235-237: How did you choose the calibration interval [-0.04;-0.008]? You need to explain how you came to choose these values as the final binary maps are based on this interval.

Revised in text. See L254-267.

To distinguish between perennial firn aquifer areas and percolation facies areas where seasonal meltwater is refrozen and stored exclusively as embedded ice, we calibrated the curve fitting algorithm using the MCoRDS-derived perennial firn aquifer locations projected on the EASE-Grid 2.0. For each grid cell we extracted V-pol T_B time series and ζ values, and for each of these calibration parameters we calculated the standard deviation (σ). We set thresholds of $\pm 2\sigma$ in an attempt to eliminate peripheral grid cells near the ice edge and near the upper perennial firn aquifer boundary where L-band emissions are influenced by morphological features, such as crevasses and exposed glacial ice, and mix with emissions from rock, land, the ocean, and adjacent percolation facies areas. We set a *minimum brightness temperature threshold of T_{min}=200, and a maximum brightness temperature threshold of T_{max}=240, and an exponential rate of normalized brightness temperature decrease threshold of $\zeta \in [-0.04, -0.008\,]$. If the calibration parameters are within the threshold intervals, the grid cell is converted to a simple binary parameter to map extent. T_B time series iteratively fit to the sigmoid function converge quickly (i.e., algorithm iterations $I \in [5, 19]$), and observations are a good fit (i.e., chi squared error statistic is $\chi 2 \in [0, 0.06]$), indicating our algorithm provides a plausible satellite-derived map of the extent of Greenland's perennial firn aquifers.*

L237 and L253: typo [-1;-0.04]

Corrected in text and figures.

L242: What about H-pol time series? You mention at L186 that you analysed the H-pol time series as well but you only fit the V-pol time series?

Clarified in text. See L242-247.

The curve fitting algorithm proceeds by smoothing V-pol T_B time series that have been partitioned by TIR T_B-derived surface freeze-up and melt onset dates, and then iteratively applying the sigmoid fit. This results in a reduced chi-squared error statistic when fitting V-pol T_B time series to the sigmoid function. The V-pol channel exhibits decreased sensitivity to changes in the volumetric fraction of meltwater as compared to the H-pol channel. We attribute these differences to reflection coefficient differences between channels. We note, however, that both channels provide reasonable results.

L267: You state that the number of iterations is between 1 and 10 but based on Figure 2, the number of iterations seems to be higher (21 at sites 3 and 4)?

Thank you for pointing this out. Figure 2 revised.

L273: Based on Figure 2, the colours corresponding to sites 1-4 are blue, cyan, red and green and not blue, teal, yellow and green L278: In the text, Test Sites 4 and 5 are reported as marked with orange and red lines but in Figure 2, Test Sites 4 and 5 are marked by the green and orange lines. Don't you mean Test Sites 3 and 5 instead (see my comment below)?

Thank you for pointing this out. Figure 2 revised.

L273-280: Aren't Test Sites 3 and 5 (red and orange lines) examples of other facies areas and Test Sites 1, 2, 4 and 6 sites with firn aquifer signatures?

Revised in text.

L311: Please state how many grid cells.

Text removed.

L287: It would be interesting to comment on how the firn aquifer extent you derived from L-band data relates to previously reported estimates of firn aquifer extent

Revised text. See L312-319.

The L-band T_B-derived perennial firn aquifer extent is generally consistent with previous C-band (5.3 GHz) satellite radar scatterometer-derived extents mapped using the Advanced SCATterometer (ASCAT) on the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Meteorological Operational A (MetOp-A) satellite (2009-2016, ~52,000 km–153,000 km, Miller, 2019), and the Active Microwave Instrument in scatterometer mode (ESCAT) on ESA's European Remote Sensing (ERS) satellite series (1992-2001, ~37,000 km-64,000 km, Miller, 2019) as well as with the C-band (5.4 GHz) synthetic aperture radar-derived extent mapped using the synthetic aperture radar on ESA's Sentinel-1 satellite (2014-2019, 54,000, Brangers et al., 2020).

L306-320: Please be more specific in your comparison to MCoRDS and Accumulation Radar-derived firn aquifers and provide some quantitative metrics.

This is not a reasonable comparison given the small size of the MCoRDS locations and the footprint of the scatterometer.

See line 91-100

*Given converging orbital passes in the polar regions, the SMAP satellite passes over Greenland several times each day, and provides nearly complete coverage during two distinct local time-of-day intervals. The rSIR algorithm combines orbital passes that occur between 8 a.m. and 4 p.m. (+/-2 hours) local time-of-day to reconstruct twice-daily (morning and evening orbital pass interval, respectively) T_B images. T_B image data are projected on the Equal-Area Scalable Earth Grid (EASE-Grid 2.0) (Brodzik et al., 2012) at a 3.125 km posting resolution or grid cell spacing. The effective resolution for each grid cell is dependent on the number of observations used in the rSIR reconstruction and is coarser than the grid cell spacing. While the effective resolution of conventionally processed T_B images posted on a 25 km grid is ~30 km, the effective resolution of enhanced resolution **T_B images posted on a 3.125 km grid is ~18 km**, an improvement of ~60%.*

See L170-176

We projected the MCoRDS-derived perennial firn aquifer locations on the EASE-Grid 2.0 at a grid cell spacing of 3.125 km. Each grid cell has an extent of ~10 km. The total number of grid cells with at least one location is 780 corresponding to an extent of ~7617 km^2; however, less than ~5% of this extent is an actual detection. The maximum number of detections in a grid cell is 50, corresponding to an extent of 0.25 km^2 or ~8% of a grid cell. These three locations are along crossing flight lines near Test Site 1 (Fig. 1). The remaining detections are along linear flight lines. The mean number of detections in a grid cell is 18, corresponding to 0.09 km^2 or ~1% of a grid cell.

See L269-276

We note, however, that the lack of a distinct L-band T_B signature that delineates the boundary between perennial firn aquifer areas and adjacent percolation facies areas and the limited number of MCoRDS-derived perennial firn aquifer locations results in significant uncertainty in the mapped extent. If V-pol T_B time series are not quite within the calibration intervals, it does not necessarily indicate that a perennial firn aquifer is not present over at least a percentage of a grid cell. A sensitivity analysis suggests that even small changes in the calibration intervals (i.e., a few K for T_{min} and T_{max} values, and a few hundredths of a percentage point for ζ values) can result in extent changes of hundreds of kilometers. Thus, the mapped extent should simply be considered a rough estimate.

Figure 1: In the caption, I think that what is labelled as Figure b) is actually Figure c). I think that it would be best to change the colour of Test Site 1 for something different than blue as the MCoRDS derived firn aquifers are also marked in blue (same for Figure 3). Also what is the difference between the yellow lines in b) and the black lines in d)? Figure 3: Idem as in Figure 1, Figure c) is labelled as Figure b here. I think that you need to clarify the legends of Figure b) and d). I guess that MCoRDS-derived firn aquifers are in blue and not in yellow and blue circles? I find it hard to understand what you are showing on b) and d)

Figure 1 and 3 revised.