Response to Referees on egusphere-2023-1556

First of all, we would like to thank Referee 3 for the approval of the manuscript. Since there is no comment from Referee 3, this document only includes the response to Referee 2. Please find the item-by-item reply below, with the original comments in *italics* and the responses in blue. All the suggested changes are implemented in the revised manuscript and we will refer to the different versions of our manuscript as V0 (original submission, 24 Jul 2023), V1 (first revision, 26 Jan 2024) V2 (second revision, 4 May 2024) and V3 (current submission, Aug 2024)

I'm slightly concerned about the way the authors replied to my comments. Several contents on which I have asked for clarification have been removed, and the depth involved in the analysis has been increased for the third time, based on a questionable search of the maximum correlation between satellite observation and target parameter that neglects the depth dependence on frequency. The rationale behind this criterion is also unclear because the authors themselves stated "the relationship between satellite parameters and firn density is complex, and simple linear relationships may not adequately describe the IMAU-FDM density based on different satellite parameters…".
Despite the pivotal changes from one revision to another, the authors obtain almost the same good results; however, without physical support and interpretation, their findings could also depend on issues in the approach, in the data organization or in the ML implementation (overfitting?). In other words, although I am favourable to the "data driven" approaches, method and results must be placed in a robust physical framework, which seems lacking here. Considering the interesting topic, I'm giving another major, in the hope the authors will provide better support for their findings.

First of all, we appreciate that the referee still finds the topic interesting. We would like to clarify our ideas in the following points:

1. Regarding the choice of the assess depth.
To avoid misunderstandings, we believe that the "physical support and interpretation" consists of two different aspects. One is whether C-band radar can observe near-surface (e.g. < 1 m depth) firn properties at all, and the other is why we changed the depths for the experiment.

Regarding the first aspect, whether C-band can observe near surface properties, we rely on a set of arguments that should support the physical interpretation in this response. The first argument is based on a new analysis in the revised V3 of the paper (added to Appendix A), where we performed a simple sensitivity analysis using the Snow Microwave Radiative Transfer (SMRT) model to understand the penetration depth of different sensors. For this experiment, we use a multi-layer snowpack of 20 m depth where the thickness of each layer is set to 40 cm. In this analysis, we perform two experiments. In the first experiment, we run SMRT for 3 locations with in situ measurements of temperature, density and grain size following Larue et al. (2021). All layers have the same firn properties in this experiment. Subsequently, in a second experiment, we disturb for each layer at a time the observed firn properties, in order to observe the impact of altering firn properties (i.e. density + 50 $kg\ m^{-3}$, grain size + 0.5mm) on different depths. The results of the sensitivity analysis (Fig. R1 below and Figure A1 in appendix of the revised manuscript V3) show that the sensitivity of both C-band backscatter and brightness temperature decreases with an increasing depth. C-band can be sensitive to density and grain size changes at more than 20m depths, whilst 19 GHz and 37 GHz are sensitive up to 6-10 m and 0.8-1 m, respectively.

This sensitivity analysis confirms the argument raised by the reviewer (i.e. deep penetration of C-band), but also confirms that, given the high sensitivity to top layers, C-band can be used to assess surface firn properties as it is definitely not transparent. It is as such in line with arguments made in other studies and that we used in previous revisions to argue for using C-band to assess surface firn properties (e.g. the study of Fraser et al. (2016) who only used the mean firn density of upper 1 m in dry zones of Antarctica to derive the relationship with C-band backscatter or Tran et al. (2008) who related backscatter intensities from Ku-band (13.575 GHz) and S-band (3.2 GHz) radar altimeter (with a theoretical penetration depth of over 10 m; Remy et al., 2015) and brightness temperatures from 23.8 GHz and 36.5 GHz to surface conditions over Antarctic firn).

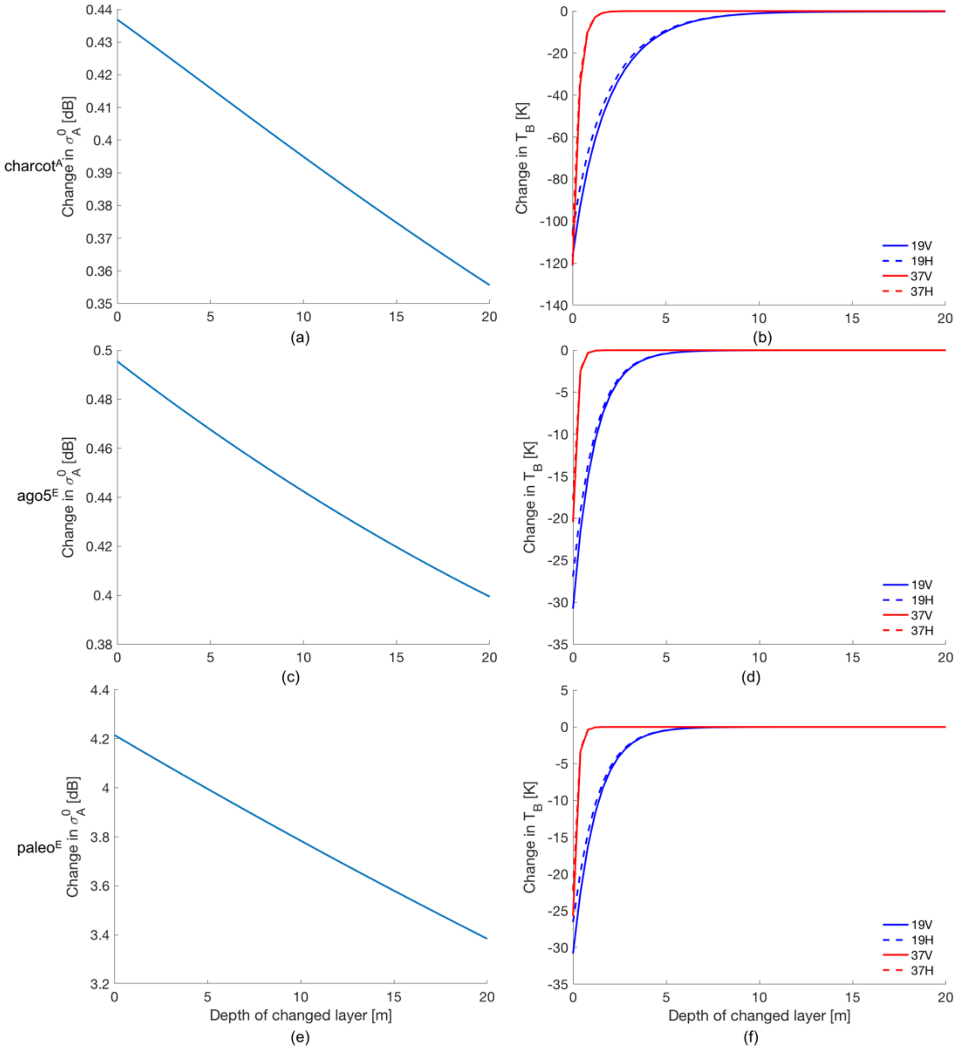

Figure R1. Sensitivity analysis using SMRT

Regarding the second aspect, namely the change of depths throughout the different versions of the manuscript, we would like to again use SMRT sensitivity experiment in combination with the depth correlation of density to explain the good results for different depths.

First, the SMRT sensitivity experiment namely shows that both radar and radiometer are sensitive to a range of depths (e.g. C-band can be sensitive to density and grain size changes at more than 20m depths, whilst 19 GHz and 37 GHz are sensitive up to 6-10 m and 0.8-1 m, respectively). Therefore, we believe that adopting the depths within 0.8 m should physically make sense.

Second, we want to stress that at near-surface depths, variations in density are typically highly correlated (e.g. if the density at 4 or 12 cm depth is higher/lower it is probably also higher/lower at 40cm or 1 m). To illustrate that, we computed the overall correlation coefficients between 4 cm density and densities at 12 cm, 40 cm, 1 m and 5 m depths from IMAU-FDM. The obtained mean correlation coefficients are 1.00, 0.73, 0.36 and 0.10, respectively. This assessment is also added to Appendix D of the revised manuscript V3.

Both these arguments (i.e. large satellite sensitivity up 80 cm and correlated density in the first meter) explain why we obtained similarly good results at depths of 4 (V0), 12 (V1) and 40 (V2) cm. Moreover, these arguments also hint at the fact that the methodology would not work at depths larger than 80 cm. Therefore, we set up another experiment in the revised V3 of the paper (added to Appendix D), to observe whether increasing the depth largely changes the results. Interestingly, as Fig. R2 of this document (or Fig. D1 in appendix of V3) shows, the temporal correspondence between RF-derived densities and IMAU-FDM densities in terms of correlation coefficient indeed becomes much lower when we increase the assessed depth from 12 cm to 1 m, especially for megadune regions where the theoretical penetration depth of 19GHz is 0.3 m according to Picard et al. (2009). Finally, at 5 m depth, the method completely loses the ability to match the temporal pattern of IMAU-FDM density, which proves that our approach is not affected by overfitting.

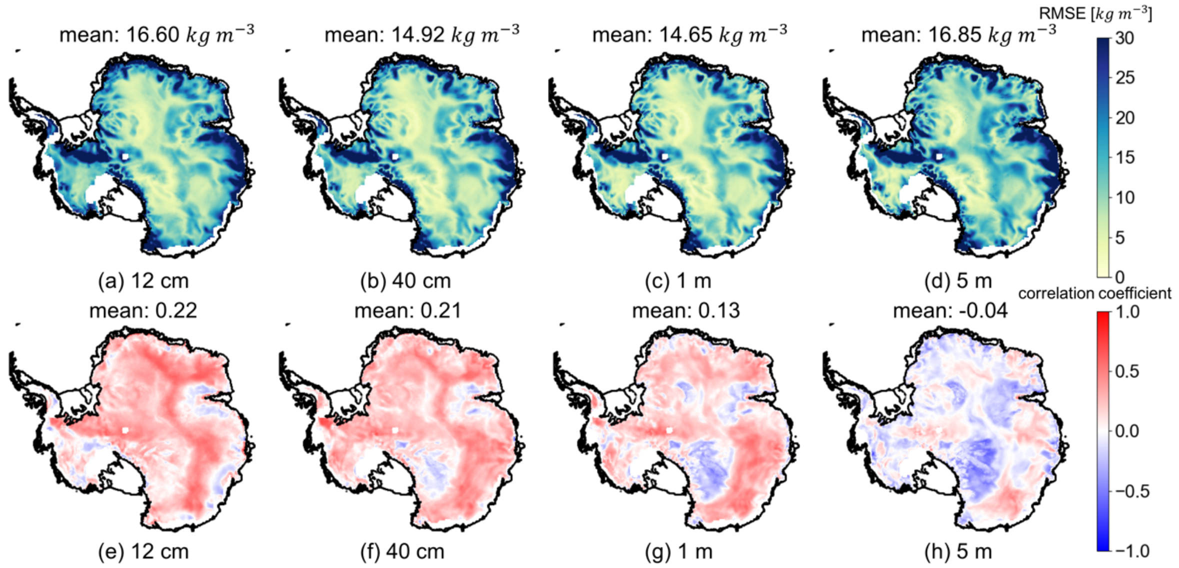

Figure R2. RMSE (upper) and correlation coefficients (lower) at different depths (12 cm, 40 cm 1 m, and 5 m, respectively).

Finally, we think that the sensitivity analysis and density depth correlation analysis provides physical support of why the method works (i.e. sensitive to firn variations in the upper meter), why it works well for different depths in the different manuscript versions (i.e. sensitive to firn variations over a range of depths and highly correlated densities at different depths in the first meter) and why it does not work for larger depths (i.e. density at deeper depths not related to near-surface density which dominates the signal).

This combination of arguments has led us to an approach in V2+V3 where we search for the optimal depth with the maximum correlation between satellite observation and target parameter that neglects. We acknowledge that this optimal depth might be different for different locations (see also Fig R2/D1), but we decided to choose one common final depth throughout the manuscript.

2. *"the depth involved in the analysis has been increased for the third time, based on a questionable search of the maximum correlation between satellite observation and target parameter that neglects the depth dependence on frequency"*

We would like to refer to the Referee's previous comment: *"it seems that, by comparing against 12 cm rather than 4 cm, some small improvements are obtained at Ku and Ka band while the C-band does not show appreciable improvements. This could go in the right direction by supporting the concern about the insufficient depth. As requested in the previous round, it would be important to provide overall correlation or determination coefficients,"* Note that here "Figure 2" refers to the revised manuscript V1. Following this discussion, we assessed the correlation between IMAU-FDM at different depths and every satellite parameter, as shown in Table 2 of the revised manuscript V2 and V3. This assessment indicated that increasing the assessed depth does not necessarily result in improvements, as suggested by the previous comments. Rather, once we apply this comparison, 40 cm returns the overall highest correlation, hence seems to be the optimal choice. Figure R1 also shows that, C-band is most sensitive to the upper firn rather than e.g. at 20 m depth.

We agree that our method does not explicitly account for different penetration depths which vary per location and sensor (Picard et al. 2009). However, the newly added sensitivity analysis (Appendix A) and correlation analysis shows that the analysis for different depths below one meter are all physically explainable (i.e. strong sensitivity) and could potentially be interchanged (i.e. highly correlated density at different depths). Similar to the previous response, we acknowledge that this optimal depth might be different for different locations (Picard et al. 2009; see also Fig. R2/D1), but we decided to choose one common final depth throughout the manuscript for clarity.

However, we appreciate the Referee for pointing out that the reasoning may not be clear. Therefore, we performed the SMRT experiment and added it to Appendix A of the revised manuscript V3. We have also added the following motivation on Line 189 of the revised manuscript:
"The reason for this comparison is that, although the theoretical penetration depth can be larger than 20 m for C-band in Antarctic dry firn (Rott et al., 1993), the surface conditions such as temperature, wind and precipitation have more impact on shallow depth of the firn layer, as well as on the satellite parameters (Tran et al., 2008; Picard et al., 2012; Champollion et al., 2013; Fraser et al., 2016). By calculating the correlation coefficients between IMAU-FDM densities and satellite parameters, we need to understand at which depth the densities cannot

be affected by the surface conditions. We also need to estimate a depth threshold from which 37 GHz cannot penetrate the firn layers hence cannot provide information on spatial and temporal variation of firn from this experiment, as the penetration ability reduces with an increasing frequency (Rott et al., 1993; Surdyk, 2002). Finally, the density at the depth where the best overall correlation between satellite observations and density time series is adopted for the RF experiment."

We also added the following discussion on Line 384 of the revised manuscript, with the hope of showing the reasoning and conclusion of this comparison more clearly:
"Despite a theoretical impact of surface climate conditions such as temperature, wind and precipitation on both satellite parameters and firn density at a shallow depth (Fraser et al., 2016), the lack of a consistent linear relationship was evident in the examination of the individual satellite observations, as the highest mean temporal correlation between satellite observations and the 40 cm IMAU-FDM firn density is 0.24."

We then added the discussion regarding the limitation of the depth to be studied on Line 413:
"Finally, our combination of satellite parameters cannot be used to assess densities at depths deeper than approximately 80 cm. This limitation is first because of the theoretical penetration depth as shown in Appendix A: a depth exceeding 80 cm is physically not meaningful for the 37 GHz microwave. Another reason for this limitation is that our study is based on the assumption that the surface climate conditions can affect both shallow-depth firn densities and satellite parameters simultaneously (Fraser et al., 2016). Firn densities at larger depth are not largely affected by surface conditions, hence our combination of satellite parameters is not applicable, even if 19 GHz and C-band microwave have a theoretical penetration depth larger than 5 m (as shown in Appendix D)."

Finally, we added the following discussion on Line 462, to clarify that our study only indicates the shallow firn densities that can be driven by climate properties, instead of showing the actual scattering mechanism:
"Our study is also mainly limited to firn densities at shallow depths where the climate phenomena have a large impact; it cannot indicate the actual scattering of firn grains, as a more complicated mechanism persists (Picard et al., 2022)."

3. *"Despite the pivotal changes from one revision to another, the authors obtain almost the same good results."*

See earlier response where we show that sensitivity is similar for a range of depths and that density variations over depth are highly correlated in the upper layers explaining "the same good results" for different depths in different revisions.

4. Removal of contents.
We agree that the manuscript has changed a lot based on the comments of the previous revision rounds. However, we want to stress that this is the result of demanded changes by the reviewers. Below we explain these changes again shortly as the motivation for these changes might have not been very clear for the reviewer.

a. The polarisation and frequency ratios

Hereby we would like to quote the first version of the Referee's comment: *"based on the information theory, the indices should not bring any additional information independent of the Tb from which they have been computed, so, also based on my experience, these indices should negligibly affect the results."* Referee 3 mentioned the same point: *"Again correlation between derived sat (PR, FR) and the Tb at 19,37 is probably high. So the importance of Pr and Fr is reduced. Most of the information contain in Pr is probably also in the Tb."* Furthermore, we adopted the ratios originally with the hope of including the findings of Champollion et al. (2013), where a relationship between hoar-crystal disappearance (characterised by an increase in 2 cm firn density) and polarisation ratios could be established at Dome C in some moments; this cannot be established in our study using any depth of modelled firn density, hence the physical base of using the Tb ratios is lacking and we removed the parameters from the newest experiment.

b. The Tb and sigma-0 anomalies

We quote the previous version of the Referee's comment: *"Figure 5 seems a bit redundant and its informative content not exceptional since the behaviours are difficult to interpret; moreover, figure 6 points out the minor contribution of these parameters in the retrieval."* We agreed that the anomalies do not contribute to the RF process, therefore removed them in the newest experiment as well.

c. The in situ densities at Dome C

According to the previous version of the Referee's comment: *"The comparison with the Dome-C data from Leduc is relevant as validation against independent data. However, the data refer to the first 2/3 cm depth and the RF has been trained for 12 cm depth…. Please further address."* Originally, we compared the 2 cm in situ density measurements with the modelled 4 cm measurements (as this is the finest resolution available from IMAU-FDM outputs), and showed the potential limitation in the IMAU-FDM densities in modelling local and temporary surface variations due to the simplification of wind patterns in the model. Such bias can potentially propagate towards 12 cm. However, we noticed that the inclusion of 2 cm in situ data (which was not provided by us), the 4 cm modelled density and the 12 cm modelled density (both provided by IMAU-FDM) can cause confusion. In addition, this figure once more intended to reproduce the Champollion et al. (2013) study by observing the trends of polarisation ratios versus surface density. Since we do not consider either surface density or polarisation ratio anymore, we decided to remove this comparison.

With all the reasoning above, we cannot agree that the contents that have been removed need further clarification. However, we appreciate the suggestion of the Referee in the previous comments to understand better the usage of Tb-derived indices for future studies. They should be helpful both in understanding the depth of firn and in assessing firn property variations. Therefore, we have added the following discussion on Line 450 of the revised manuscript:

"Finally, our study only demonstrated a simple approach in understanding the long-term correlation between firn density and satellite parameters, based on climate conditions that potentially affect them (Fraser et al., 2016). However, due to the different penetration abilities of different microwave frequencies (Surdyk, 2002), future research can benefit from a more quantitative assessment regarding to what extent the penetration depths and other climate parameters affect the results. Better parametrisation of satellite observations which can

indicate the variation of firn depth (Santi et al., 2012a; Michel et al., 2014) as well as surface and depth hoar-crystal formation and disappearance (Champollion et al., 2013) can also be adopted."

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