Response to Editor

Thank you for the substantial revision and detailed responses. The manuscript has improved, particularly in its more cautious interpretation of the optimized grain-size parameter and the FAC-related analysis. I also note that both reviewers are satisfied with the revision.

We thank the editor for clearly identifying these remaining concerns. We agree that the interpretation and temporal structure of the inversion, its sensitivity to prescribed assumptions, the documentation of the Figure 2 experiments, the scope expressed by the title, and the reproducibility statement required further clarification. We have therefore revised the manuscript substantially. Please find below our point-by-point responses. All line numbers cited below refer to the clean revised manuscript, not to the track-changes version.

1. However, some of my central initial concerns remain. The optimized parameter is fitted to ASCAT observations but is not independently validated which should be noted in the abstract.

   We agree that the absence of independent validation needed to be stated explicitly in the abstract. Although the previous manuscript already discussed this limitation in the Results and Discussion, it was not sufficiently visible in the abstract. In the revised manuscript, we have therefore added the following sentence to the abstract: *"The retrieved parameter provides an observationally constrained measure of effective firn microstructure within the adopted FDM–SMRT framework, although independent validation is required before interpreting it as an absolute physical grain-size measurement."*

   This revision appears on **page 1, lines 10–12** of the revised manuscript.

2. Please clarify the inconsistency between the stated annual optimization and Eq. 3, which appears to minimize the mismatch across all years.

   We agree that the previous formulation of Eq. 3 did not make the annual structure of the optimization sufficiently explicit and could be interpreted as fitting one parameter across the full 2007–2021 period. We therefore revised Eq. 3 to express the objective directly in terms of the annual JJA-mean simulated and observed backscatter in linear units. The optimization is performed independently for each year, yielding one optimized correlation length per grid cell and year (**page 8, lines 231–242**).

   We also clarified briefly how the optimized annual correlation length is converted to the reported effective grain-size parameter using Eq. 2 and the corresponding same-year JJA density profiles (**page 9, lines 243–245**). In addition, Eq. 2 and its accompanying text were expanded to describe more precisely the correlation-length-to-effective-grain-size conversion used in the analysis, including its density dependence and physical interpretation. This was a technical clarification of the implemented method rather than a change to the underlying analysis (**page 6, lines 166–178**).

3. The manuscript should also better quantify how uncertainties in prescribed density, layering, ice lenses, surface roughness, and model forcing may affect the retrieved grain-size parameter.

   We agree and have addressed this concern through a substantial new perturbation analysis, which strengthens the manuscript by directly quantifying the robustness of the retrieval to key prescribed assumptions.

   A new Methods subsection, **"Perturbation analysis of the effective grain-size retrieval,"** uses the high-FAC Ross Ice Shelf site as a controlled dry-firn benchmark. This setting reduces the influence of competing melt and saturation processes and allows individual assumptions to be tested systematically. The experiment is intended as a representative sensitivity assessment for this dry-firn setting, rather than an Antarctic-wide probabilistic uncertainty estimate. The benchmark selection, baseline construction, and reinversion procedure are described on **pages 9–10, lines 270–291**.

   We evaluate five one-at-a-time perturbation categories:

   - a $\pm 5\ \%$ change in prescribed porosity and corresponding density;
   - an increase in vertical aggregation from 8 to 16 cm;
   - insertion of an idealized 8 cm dense layer at approximately 0.5, 1.0, and 2.5 m depth;
   - surface-related ASCAT target offsets of ± 0.5dB, together with extended ± 1.0dB stress tests; and
   - replacement of the mean profile by the complete coldest and warmest annual JJA profiles.

   The last test includes concurrent interannual differences in density, temperature, liquid water content, and their vertical distributions, rather than varying temperature alone. The perturbation definitions and quality-control criteria are described on **page 10, lines 292–309,** and **page 11, lines 310–318**.

   The quantitative results are presented in **Table 2 and Sect. 4.4 on pages 18–19, lines 460–478**. The primary ± 0.5dB surface-related offsets produce the largest response (-4.98 to $+5.41\ \%$), followed by interannual full-profile variability (up to $+3.72\ \%$) and idealized dense layering ($+1.62$ to $+2.22\ \%$). The porosity perturbations produce changes below $1\ \%$, while increasing the vertical aggregation produces a change of only $-0.09\,\%$. The extended $\pm 1.0\text{dB}$ stress tests produce changes of -9.57 and $+11.33\,\%$ and are reported separately from the primary comparison.

The implications are discussed on **pages 24–25, lines 594–618**. The results show that the Ross retrieval is comparatively robust to moderate density and vertical-discretization changes, but more sensitive to dense layering, interannual profile variability, and unresolved near-surface scattering. We also relate this hierarchy to previous work on stratigraphy, roughness, sastrugi, and snow-transport effects.

Complete scenario-level values and optimization diagnostics are provided in **Appendix Table C1 on page 34, introduced at lines 843–845**.

4. Figure 2 requires clearer site-selection criteria, coordinates, consistent symbols between panels, and a simpler axis design. The Larsen-B example must be identified more precisely, with evidence that the selected 27 km cell represents an ice-shelf remnant rather than sea ice.

   We have revised both the methodology and Figure 2 presentation. The five 27 km grid cells are now selected according to three explicit criteria:

   - they span the observed range of long-term winter-mean FAC conditions across Antarctic ice shelves;
   - they contain complete ASCAT and IMAU-FDM records for 2007–2021; and
   - they lie within the analysis ice-shelf mask and remain after the calving-front screening.

   The sites comprise two high-FAC cells, one intermediate-FAC cell, and two strongly depleted cells. We also clarify that they are illustrative examples of contrasting regimes rather than a statistically representative sample. These criteria and qualifications appear on **page 7, lines 195–203**. The coordinates, long-term mean FAC values, and FAC classifications of all five sites are now reported in **Table 1 on page 8**.

   Because the Larsen-B remnant borders an embayment that has contained both seasonal and multi-year landfast sea ice, we carried out an additional spatial verification of the complete 27 km footprint. The footprint was compared against annual Antarctic coastlines for every year from 2007 through 2021. The full footprint remained within the mapped Antarctic ice extent in all 15 years, its minimum cell-edge distance from the annual coastline was 1.6 km, and its center lies within the Larsen-B polygon of the ice-shelf mask. These tests support its interpretation as persistent Larsen-B remnant ice rather than adjacent sea ice. This verification is described on **page 7, lines 204–211**.

   Figure 2 has also been revised visually:

   - the five sites use site-specific colors in both the map and response curves;

- the observed ASCAT values use coloured circles corresponding to the same site colors;
- panel (b) uses a single backscatter axis;
- the caption explicitly explains the relationship between the map locations, curves, circles, and FAC values.

The revised figure and caption appear on **page 15**. The associated interpretation appears on **page 14, lines 384–414**.

5. The title remains too broad because the study primarily estimates one ASCAT-conditioned effective grain-size parameter rather than firn properties generally. FAC should also be defined at first use in the abstract.

   We agree that the previous title was too broad because the inversion estimates one principal microstructural quantity rather than firn properties generally. The revised title is:

   "Inferring Effective Firn Grain Size across Antarctic Ice Shelves from ASCAT Observations"

   The revised title appears on **page 1**. It now identifies the primary quantity being inferred, includes "effective" to distinguish it from a direct measurement of individual physical grains, and retains the observational basis of the method. We have also now defined FAC at first use in the abstract on **page 1, lines 12–14** as firn air content, specifically the vertically integrated pore-air content of the firn column.

6. Finally, the code and data needed to reproduce the main results should be deposited in a permanent, versioned repository before acceptance, rather than being available only on request or after review.

   We agree that the code and data required to reproduce the principal results should be publicly available in a permanent and versioned repository before acceptance. We have therefore archived the analysis and inversion code, processed model inputs, optimized effective grain-size dataset, perturbation-analysis outputs, and figure-ready data in Zenodo: **Code and data for Inferring Effective Firn Grain Size across Antarctic Ice Shelves from ASCAT Observations, version 1, DOI: 10.5281/zenodo.21499624.** The archived release is permanently versioned and corresponds to the manuscript version submitted for review. The Code and data availability statement has been revised accordingly on **page 30, lines 798–804**.

Additional manuscript-wide consistency revisions

To ensure that the revised annual inversion and the new perturbation analysis are described consistently throughout the manuscript, we also revised several connected passages. We clarified the distinction between prescribed firn-profile variables and the experiment-specific microstructural parameter (**page 4, lines 110–115**), updated the Methods overview to reflect the complete revised workflow (**page 5, lines 130–146**), and clarified the single microstructural degree of freedom and its implementation in the forward-sensitivity experiments (**page 7, lines 188–194; pages 7–8, lines 212–230**). We also integrated the perturbation analysis into the broader interpretation of the study's contributions, retrieval robustness, and unresolved surface-related scattering (**pages 22–23, lines 529–548; pages 26–27, lines 671–680; pages 26–27, lines 704–720**). Finally, to maintain consistency with the stated validation scope, the Sentinel-2 melt-pond dataset is now described as an independent contextual indicator rather than as a validation metric (**page 5, lines 123–125**).