

Response to Reviewer 2

I debated between major and minor for this paper but ultimately decided on minor. I believe the research objective is extremely important. Using ASCAT data to constrain grain size evolution on Antarctic ice shelves addresses a real gap in firn modeling. The knowledge gained about how grain size influences microwave backscatter would genuinely help progress related research on firn permeability and meltwater retention.

That said, there are substantive issues to address. The single-layer grain-size assumption needs more discussion given vertical processes like refreezing. The FAC retrieval ambiguity at low backscatter values requires clarification. Several methodological aspects such as temporal aggregation choices, computational feasibility, and some interpretive framing etc can be strengthened.

The basic idea of the conducted research is good and the contributions are valuable. However, I strongly recommend addressing the reviews in the subsequent revisions before accepting it for the publication.

We thank the reviewer for the careful reading of our manuscript and for the thoughtful and constructive comments. We appreciate the positive assessment of the scientific objective and the recognition that the study addresses an important gap in firn modeling using ASCAT observations. Several aspects of the methodological framing, interpretation, and scope of the conclusions can indeed be clarified further. In the revised manuscript, we will address these points by strengthening the discussion of key assumptions, sharpening the interpretive framing of the retrieved parameters, and clarifying the limitations and intended applications of the framework. Please find below our point-by-point responses (in red).

Please find attached my detailed comments.

1. **Column-wise grain-size assumption may mask physically meaningful heterogeneity.**

The optimization treats the entire ~20 m ASCAT-sampled column as having a single uniform grain size. While this is justified by under-representation concerns (line 513-514), it creates a conceptual tension: if you are optimizing to match observations, why not allow some vertical structure? The authors acknowledge depth-dependent grain size matters (lines 520-522) but dismiss multi-layer retrieval as causing “optimizer collapse”. This is a significant limitation that deserves more than brief mention.

The assumption of a single column-wide grain-size parameter is a simplification and cannot represent the full vertical heterogeneity of firn microstructure. The manuscript

already acknowledges this limitation in the Methods and Limitations sections, where the inversion is defined as targeting a single, column-wide grain-size parameter for the upper ~20 m sampled by ASCAT, rather than a depth-resolved grain-size profile. It also notes that depth-dependent grain-size variability is important, but that a constant-with-depth inversion was adopted to avoid an under-represented inverse problem and optimizer instability. However, the physical implications of this simplification are not yet explained clearly enough, and we will make this more explicit in the revised manuscript.

- What kinds of physical processes are likely hidden by this simplification (e.g., refreezing layers, metamorphism gradients)?

The main processes likely obscured by this assumption include refreezing layers, vertical metamorphic gradients, and depth-dependent changes in microstructure associated with firn densification and melt-refreeze events.

- Whether the retrieved parameter should be interpreted as an effective value weighted toward certain depths based on scattering physics?

We interpret the retrieved quantity as an effective ASCAT-conditioned parameter, whose meaning is weighted toward the parts of the upper firn column that contribute most strongly to C-band volume scattering within the adopted FDM-SMRT framework.

- What if we completely ignore the vertical structure, how much confidence will you put on your spatial patterns?

We place most confidence in the large-scale spatial patterns as first-order, footprint-scale effective patterns, especially in regimes where the forward sensitivity analysis indicates stronger identifiability, while we do not interpret them as depth-resolved grain-size truth.

We will revise the Limitations section accordingly to make clearer that this assumption reflects a trade-off between physical realism and inversion stability. We will also note more explicitly that even simple depth-varying alternatives (such as an exponential profile) would remain underconstrained with the current observational setup, and that relaxing this assumption would therefore require additional observational constraints, for example from future multi-frequency and/or depth-resolved approaches.

2. ANOVA variance partitioning assumes additivity that may not hold.

The manuscript partitions backscatter variance into FAC, grain size, their interaction, and residual components (Section 3.4). The assumption of additive main effects with a small interaction term (Fig. 5a) is presented as finding, but this has important

implications. If the relationship between backscatter and these drivers is not truly additive, then partitioning may be misleading regardless of whether it is “conditional.” Consider explicitly stating that variance partitioning assumes linear(izable) relationships and discuss what non-additive physics might look like.

ANOVA-based variance partitioning relies on an additive statistical decomposition and therefore cannot represent all potentially non-additive physical interactions between grain size, FAC, and backscatter. In the revised manuscript, we will make this limitation more explicit in the Methods and Limitations sections by clarifying that the variance partitioning is used here as a linearizable, first-order diagnostic within the adopted framework, rather than as a complete physical decomposition.

More specifically, we will state more clearly that the analysis assumes approximately additive relationships over the sampled range of interannual variability and is therefore not intended to imply that the underlying firn–microwave physics are strictly additive. We will also add a short discussion of what non-additive behavior could look like in this context, for example when grain size and FAC co-evolve during melt–refreezing transitions, when ice saturation introduces threshold-like changes in scattering behavior, or when layering and near-surface structure modify the sensitivity of backscatter to one variable depending on the state of another. In such cases, the statistical partitioning may not map cleanly onto separable physical controls.

We will therefore clarify that strongly non-additive firn physics are not fully captured by this diagnostic interpretation, while also noting that investigating such behavior more directly would be a valuable direction for future work.

3. The “proof of concept” FAC retrieval curve has an unresolved ambiguity problem.

The adapted inverted U-curve (Fig. 6) is presented as a way to infer FAC from backscatter once grain size is controlled. But the two-branch ambiguity at low backscatter values remains fundamentally problematic.

The manuscript mentions using “simple, independent priors” (lines 470-472) but does not clarify how often these would be needed or whether they are actually available across the Antarctic domain. In addition, are there any other ways to deal with this ambiguity?

The two-branch ambiguity at low backscatter values is a fundamental limitation of the present proof-of-concept FAC interpretation, and we will make this more explicit in the revised manuscript. In particular, we will revise the discussion around Fig. 6 to clarify more clearly where this ambiguity arises, how dependent the present formulation is on external information in those cases, and why the FAC-oriented

interpretation should still be viewed as a proof of concept rather than a standalone retrieval.

More specifically, we will explain that independent priors are mainly needed in the low-backscatter regime where the inverted-U relationship permits both a depleted, low-FAC branch and a dry, high-FAC branch, whereas the locally monotonic part of the curve is much less ambiguous. We will also state more explicitly that such priors are not uniformly or consistently available across the Antarctic domain. The manuscript already mentions examples of such priors, including melt-pond presence, MoA climatology, field-based grain size where available, and firn-model guidance, but their practical availability and role in resolving the ambiguity will be described more clearly.

We will also note that these priors are not the only possible route to reducing the ambiguity, and that future extensions could incorporate additional multi-sensor and/or multi-frequency constraints, or more explicit integration with firn-model state estimates. The revised discussion will therefore frame the backscatter-FAC relationship as becoming more interpretable once grain-size-driven scatter is reduced, while making clear that the ambiguity remains unresolved in the current proof-of-concept formulation.

4. Comparison between IMAU-FDM and optimized grain size may conflate model error with physical reality.

The manuscript presents discrepancies between IMAU-FDM grain sizes and optimized values as evidence that the model needs improvement (e.g., lines 540-548). But this comparison assumes:

The optimization retrieved a “true” value, yet we have established it is an effective, ASCAT-conditioned parameter. IMAU-FDM errors are solely due to grain-size physics when they could also reflect errors in temperature history, accumulation, or other drivers that feed into the model.

Consider reframing: instead of “model underestimates/overestimates,” discuss whether discrepancies indicate inconsistency between modeled and observed scattering behavior, which could stem from multiple sources.

This comparison deserves more careful framing in the manuscript. In the revised manuscript, we will reframe the comparison between IMAU-FDM grain size and the optimized grain-size parameter more carefully so that it is not interpreted as a direct comparison between model error and physical truth. Specifically, we will revise the relevant discussion to make clearer that the optimized quantity is an ASCAT-conditioned effective parameter, and that discrepancies with IMAU-FDM should

therefore be interpreted as inconsistencies between modeled firn-state/scattering behavior and ASCAT-conditioned effective retrievals within the adopted framework. We will also clarify that such inconsistencies need not arise from grain-size parameterization alone, but may also reflect uncertainties in temperature history, accumulation forcing, density evolution, and other modeled inputs that affect the simulated scattering response. Accordingly, where the manuscript currently uses phrases such as “IMAU-FDM underestimates/overestimates grain size”, we will revise the wording to emphasize that these are framework-dependent discrepancies rather than direct evidence that the model departs from physical truth.

5. The backscatter-FAC relationship analysis does not account for frequency dependence.

C-band ASCAT is used throughout, but microwave scattering physics is inherently frequency-dependent (as also noted in lines 523-525). While you are not expected to do multifrequency inversion now, consider:

Briefly acknowledging that FAC interpretation may differ at other frequencies. I would also clarify whether C-band’s particular sensitivity profile limits or biases certain conclusions about grain-size versus FAC control.

In the revised manuscript, we will clarify more explicitly that the present analysis is specific to C-band ASCAT, and that the interpretation of the backscatter-FAC relationship may differ at other microwave frequencies. The current framework is intended to interpret firn-state controls within the observational space of ASCAT, rather than to imply that the balance between grain-size and FAC sensitivity is frequency-independent.

More specifically, we will state that the relative sensitivity to grain size and FAC depends on the penetration depth and scattering characteristics of the observing frequency. We will also clarify that, because C-band sensitivity varies with firn state and penetration conditions, it may be more responsive to grain-size-related variability in some regimes and to FAC/density-related variability in others.

We will add a brief discussion in the Discussion section to make clear that the FAC-oriented interpretation developed here should not be assumed to transfer directly to other frequencies, and that extending the framework using multi-frequency observations would be an important direction for future work.

6. Temporal aggregation choices lack justification.

The study uses winter-mean values throughout. This choice has implications:

In the revised manuscript, we will justify the use of winter aggregation more explicitly in the Data and Methods sections by clarifying both why winter (JJA) was selected for

the inversion framework and what seasonal information is not resolved under this choice.

- Why winter specifically? Does this avoid melt-related physics that might be more relevant to hydrofracture concerns?

The use of winter (JJA) mean backscatter was intended to minimize the direct influence of active melt, transient liquid water, and short-lived seasonal effects, thereby isolating a more stable interannual signal related to firn structure and microstructure within the ASCAT–FDM–SMRT framework. In that sense, winter aggregation is used to reduce melt-season contamination of the inversion, even though melt-related processes remain highly relevant to firn depletion and hydrofracture more broadly.

- What seasonal variability is being lost by aggregating to single values per year/season?

This choice comes at the cost of losing seasonal information. By aggregating to winter means, we do not resolve melt-season timing, short-term refreezing events, seasonal transitions, or sub-seasonal variability in firn state and backscatter. The present study therefore focuses on stable year-to-year structural contrasts rather than seasonal firn evolution.

7. The “effective grain-size” parameter definition is circular.

The manuscript defines the optimized value as an “ASCAT-conditioned effective parameterization” (line 436).

In the revised manuscript, we will clarify more explicitly that the optimized grain-size parameter should be understood primarily as an ASCAT-constrained retrieval parameter within the adopted FDM–SMRT framework, rather than as a direct microphysical grain-size measurement or as a classical effective-medium property derived independently of the observations.

This framing is honest but creates interpretive issues:

- An “effective” parameter in radiative transfer typically means something derived from upscaling microphysical properties, but here it’s being inverted from observations.

This distinction is important here. Our intention is not to use “effective” in the classical radiative-transfer sense of an independently derived upscaled property, but to refer to a parameter inferred through inversion from ASCAT observations within the adopted framework.

- Consider clarifying whether this should be thought of as a retrieval constrained by ASCAT, or an effective medium property that happens to match ASCAT when plugged into the forward model.

It should primarily be understood as a retrieval constrained by ASCAT within the adopted FDM–SMRT framework. We will revise the text accordingly so that this interpretation is stated more directly and does not suggest a direct physical grain-size truth.

8. Comparison with previous work lacks depth.

The manuscript cites Alley et al. (2018) and Dattler et al. (2024) but doesn't systematically compare:

In the revised manuscript, we will strengthen the comparison with previous work (Alley et al., 2018; Dattler et al., 2024) to clarify more explicitly how the present framework relates to earlier FAC-inference approaches and what it adds beyond the already established sensitivity of ASCAT to firn-state variability.

- Whether their FAC-inference approach would have produced similar results if applied to the same domain/data.

This is an important contextual question. While we do not perform that direct comparison here, we will clarify that the present study is designed to complement rather than replicate such approaches, by showing how explicit treatment of grain-size variability affects the interpretation of ASCAT backscatter across Antarctic ice shelves.

- What advantages / disadvantages the current grain-size-constrained approach has over purely empirical backscatter - FAC relationships.

We will discuss more clearly that the main advantage of the present framework is the gain in physical interpretability that comes from first constraining an effective ASCAT-conditioned grain-size parameter and then examining how reducing grain-size-driven scatter changes FAC-oriented interpretation. The corresponding limitation is that this approach depends more strongly on the adopted forward-model assumptions than a purely empirical backscatter–FAC relationship.

- How this work advances beyond simply confirming that ASCAT is sensitive to both variables (which was already known).

We will clarify that the advance of this work is not simply the confirmation that ASCAT is sensitive to both grain size and FAC, but the use of a physics-based FDM–SMRT framework to constrain grain-size-related variability and examine how this may facilitate future FAC-oriented interpretation across Antarctic ice shelves.

9. Surface roughness effects are acknowledged but not tested.

The manuscript mentions unmodeled surface processes contribute to residual variance in dry, high-FAC zones (lines 497-502) and proposes adding a rough-surface scattering module as future work. But, without testing whether including this would actually reduce residuals, the attribution remains speculative. Can you clarify this part?

In the revised manuscript, we will clarify more carefully how the residual contribution in dry, high-FAC regimes is interpreted, so that the discussion distinguishes more clearly between plausible explanation and demonstrated mechanism.

The current attribution of part of the residual variance in dry, high-FAC regimes to unmodeled surface processes remains interpretive rather than directly tested within the present framework. Our intention is not to claim that roughness has already been demonstrated as the dominant cause of the residual, but rather to identify it as a plausible contributor based on the spatial pattern of the residual signal and prior literature on ASCAT sensitivity to near-surface processes (Cartwright et al., 2022; Poizat et al., 2024). In the revised manuscript, we will soften the wording to make clear that surface roughness, snowdrift, and related near-surface controls are presently hypotheses consistent with the residual structure, rather than mechanisms directly tested here.

We will also clarify that the proposed inclusion of a rough-surface scattering module is intended as a future route to test whether explicitly accounting for such processes reduces the residual contribution, rather than as a demonstrated result of the present study.

10. The ASCAT footprint size creates spatial averaging issues.

At 27 km resolution, each grid cell represents significant spatial heterogeneity:

In the revised manuscript, we will clarify more explicitly in the Limitations section that the inversion is performed at the 27 km RACMO/IMAU-FDM grid scale and therefore yields a spatially averaged, footprint-scale effective parameter.

- Could different parts of the footprint be in different regimes, making the single grain-size assumption even less valid?

Yes. At Antarctic-ice-shelf scale, firn properties are primarily shaped by broad climatic setting, but local firn conditions may vary over much shorter length scales than the ASCAT footprint. The retrieved quantity should therefore be interpreted as a spatially averaged, footprint-scale effective parameter rather than as a fully resolved representation of sub-grid firn heterogeneity. In that sense, sub-footprint regime mixing can make the single grain-size assumption less representative of local variability, especially near regime transitions.

- Is there any literature of whether regime transitions within footprints affect results?

While this effect is not explicitly quantified for the present Antarctic firn-retrieval setting, the broader microwave snow/firn literature shows that vertical stratigraphy, heterogeneity in grain size and density, anisotropy, and near-surface variability can influence microwave scattering behavior and its interpretation (Leinss et al., 2016; Tsang et al., 2022; Shukla et al., 2024). We will therefore frame sub-footprint regime transitions as a plausible source of uncertainty rather than as a demonstrated bias in the present study.

We will also note that an important avenue for future work would be to adapt and test the inversion framework using higher-resolution active microwave C-band data, such as Sentinel-1, in order to assess whether regime mixing within coarser ASCAT footprints materially affects the retrieved effective parameter.

11. The manuscript does not discuss potential aliasing between FAC and grain size.

While ANOVA suggests small interaction effects, this is based on a specific dataset and framework. If both variables are changing simultaneously (e.g., during melt seasons), could their effects be partially aliased even if the forward model treats them as separate?

In the revised manuscript, we will clarify more explicitly that the ANOVA interaction term should not be interpreted as proof that aliasing between FAC and grain size is absent, and that some degree of confounding may remain when both variables evolve together.

Even though the forward model treats grain size and FAC as conceptually distinct controls, the observational signal may still contain co-varying effects that are difficult to separate perfectly, especially when firn properties evolve together through melt-refreezing processes (Veldhuijsen et al., 2024). In that sense, the small interaction term in the present analysis should not be interpreted as demonstrating complete separability between these controls, but rather as the result obtained within the sampled interannual variability and the adopted inversion framework.

We will therefore add explicit clarification in the Methods and Limitations sections that some degree of aliasing may remain when FAC and grain size co-vary, and that the current variance partitioning should be interpreted accordingly. We will also note that future multi-frequency observations may help reduce such ambiguity by sampling firn structure with different penetration depths and sensitivity profiles across firn regimes.

12. The manuscript does not clearly distinguish between diagnostic and prognostic capabilities.

The work is presented partly as showing how ASCAT could contribute to FAC-oriented monitoring (line 551).

In the revised manuscript, we will distinguish more explicitly between the diagnostic scope of the present framework and the additional development that would be required for prognostic use.

However:

- Diagnostic capability (describing current state) does not necessarily imply prognostic capability (predicting future changes or responding to perturbations).

That distinction is important here. The present framework is intended as a diagnostic tool: it relates ASCAT backscatter to firn-state variability and retrieves an effective ASCAT-conditioned parameter that is consistent with the observed scattering behavior within the adopted FDM–SMRT framework. This does not by itself imply prognostic capability.

- Consider clarifying what kinds of applications the approach is actually suited for versus what would require additional development.

In its current form, the framework is suited to diagnostic and monitoring-oriented applications, such as interpreting present firn-state variability, identifying regimes where the inversion is more or less informative, and supporting FAC-oriented interpretation once grain-size-driven scatter is reduced. By contrast, predictive applications, such as forecasting future firn evolution or system response to perturbations, would require additional development, including explicit prognostic coupling to firn evolution, stronger external validation, and treatment of unresolved processes and ambiguities.

We will therefore revise the Discussion and Conclusions to make this distinction more explicit, so that monitoring and diagnostic interpretation are presented as the primary applications of the current framework, while prognostic use is identified as a future extension rather than an implication of the present study.

13. The optimized grain sizes are presented without assessing whether they represent physically realistic firn states.

In the revised manuscript, we will expand the discussion of the physical plausibility of the optimized values in the Discussion and Limitations sections so that their interpretation is more clearly framed within the adopted FDM–SMRT inversion framework. In particular, we will clarify more explicitly in which regimes the optimized values can be interpreted with greater confidence, where they require greater

caution, and how this relates to forward-model sensitivity and the limited availability of independent validation.

- In ice-saturated regions ($FAC \approx 0$), what range of grain sizes should be expected? Are the retrieved values consistent with ice crystal growth physics under those conditions?

The physical interpretation is especially delicate in these regions. After reviewing the literature, we find that there is no well-established observational Antarctic benchmark range for grain size specifically in ice-saturated firn. Veldhuijsen et al. (2024) use a refreezing grain size of 0.25 mm in IMAU-FDM, while also noting that the absence of a maximum grain-size constraint can lead to very large, modeled grains in depleted old ice. Broader firn literature, including Amory et al. (2024), indicates that wetting and water saturation promote rapid grain coarsening. In the revised manuscript, we will therefore clarify that the optimized values in such regions require especially cautious interpretation as effective scattering parameters within the adopted framework.

- The IMAU-FDM model “lacks a maximum grain size constraint” in depleted areas (line 547). Does this imply optimized values could also become unphysically large, or does the ASCAT inversion naturally constrain them?

The absence of a maximum grain-size constraint in IMAU-FDM does not automatically imply that the optimized values behave similarly. The inversion is tied to the observed ASCAT response and the forward-model sensitivity, so the optimized parameter is constrained by the backscatter misfit rather than by unconstrained long-term grain growth. We will make this distinction clearer in the revised manuscript.

- In high-FAC, dry-snow regions where FAC is >20 m and temperature is very low, are the retrieved small grain sizes (<0.5 mm) consistent with observed metamorphism rates in such conditions?

At present, we regard these small values as qualitatively plausible for cold, dry firn with limited melt influence, but not yet as independently validated benchmarks. The manuscript already notes that these regions show closer agreement between optimized and IMAU-FDM grain size and includes a limited plausibility comparison with available in-situ observations in dry-snow conditions. In the revised manuscript, we will strengthen this discussion to clarify that the small, optimized values in cold, high-FAC regimes are qualitatively consistent with less melt-affected firn and slower metamorphic evolution, while still requiring cautious interpretation and further external validation.

14. Computational feasibility of scaling the methodology not discussed.

The paper mentions using the DelftBlue supercomputer with 16 cores allocated per grid point (line 508) but doesn't address whether this approach is computationally feasible for operational or large-scale applications. This is relevant because if the framework is intended as a "complementary monitoring metric" (line 557), it will be useful to know whether it's practically deployable or remains primarily a research tool.

In the revised manuscript, we will clarify this point more explicitly in the Limitations and Future Scope section so that the present implementation is clearly distinguished from a practically deployable operational product.

In its current form, the framework should be regarded primarily as a research tool designed to test the physical consistency and interpretability of the inversion at Antarctic-ice-shelf scale, rather than as an already operationally deployable system. We will make this distinction clearer in the revised manuscript and explicitly state that the phrase "complementary monitoring metric" should be understood as a research-oriented pathway, not as a claim of current operational readiness.

We will also add a short discussion of what would be needed to improve scalability in future, including reduced-order formulations, surrogate or emulator approaches, lookup-table strategies, or more selective regional/temporal updating. This will make clearer which aspects of the current framework are already demonstrated at research scale and which would require additional methodological development before routine large-scale deployment becomes feasible.

15. Typographical Issues.

- In Section 4.2, at line 305, the word "in" is duplicated into "in in".
- Inconsistent use of "Antarctic-ice-shelf-wide" vs "AIS-wide".
- In some instances, "FAC × GS" is written as "FAC×GS" (without spaces around '×').
- Invalid URL of Alley et al., 2018 in the References. It would be worth double checking and fix similar errors (if any).

In the revised manuscript, we will correct the duplicated word in Section 4.2, standardize the terminology used for Antarctic-ice-shelf-wide versus AIS-wide throughout the manuscript, and make the formatting of FAC × GS consistent wherever it appears. We will also check the references and URLs carefully, including the Alley et al. (2018) entry, and correct any similar formatting or reference errors that remain in the manuscript.

References

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