

Review of

A Physics-based Framework to Infer Firn Properties on Antarctic Ice Shelves from ASCAT Observations

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. Consider adding a paragraph discussing:

- What kinds of physical processes are likely hidden by this simplification (e.g., refreezing layers, metamorphism gradients)?
- Whether the retrieved parameter should be interpreted as an effective value weighted toward certain depths based on scattering physics?
- What if we completely ignore the vertical structure, how much confidence will you put on your spatial patterns?

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.

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?

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.

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 multi-frequency 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.

6. **Temporal aggregation choices lack justification.**

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

- Why winter specifically? Does this avoid melt-related physics that might be more relevant to hydrofracture concerns?
- What seasonal variability is being lost by aggregating to single values per year/season?

7. **The “effective grain-size” parameter definition is circular.** The manuscript defines the optimized value as an “ASCAT-conditioned effective parameterization” (line 436). 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.
- 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.

8. **Comparison with previous work lacks depth.**

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

- Whether their FAC-inference approach would have produced similar results if applied to the same domain/data.
- What advantages / disadvantages the current grain-size-constrained approach has over purely empirical backscatter - FAC relationships.
- How this work advances beyond simply confirming that ASCAT is sensitive to both variables (which was already known).

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?

10. **The ASCAT footprint size creates spatial averaging issues.**

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

- Could different parts of the footprint be in different regimes, making the single grain-size assumption even less valid?
- Is there any literature of whether regime transitions within footprints affect results?

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?

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). However:

- Diagnostic capability (describing current state) does not necessarily imply prognostic capability (predicting future changes or responding to perturbations).
- Consider clarifying what kinds of applications the approach is actually suited for versus what would require additional development.

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

- 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 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?
- 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?

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.

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).