General comments

In this paper the authors present a dense media radiative transfer model to characterize C-band backscatter through a snowpack over a rough soil surface. After the model is demonstrated, modeled backscatter is compared to timeseries of C-band backscatter data from Sentinel-1 at several sites in the European Alps. The general topic of the paper is highly relevant because there are a number of open questions related to the potential for Sentinel-1 measurements of snow properties.

I can identify two main issues with the current manuscript. First, some of the potential conclusions are obscured by a lack of precise language. The terms snow, snow cover, snow packs, and SWE are used somewhat interchangeably throughout the introduction, and in some cases erroneously (see specific comments). Later, much of the text discusses snow in terms of snow depth but figures usually show SWE instead. Specific and precise language is important here so that the community can start to build consensus around the possibilities and limitations of using C-band data to measure snow properties. Issues throughout the manuscript must be addressed before the paper is ready for publication.

The second main issue is that it appears much of the modeling work presented here was already published by Zhu et al. (2023). For example, Figure 5 in this manuscript appears to be an exact replica of Figure 2 in Zhu et al. (2023) and Figure 8 here is a replica of their Figure 11. In my view, much of Section 3 in this manuscript could be replaced by a reference to Zhu et al. instead. In this case the main contribution of the current manuscript would be in Section 4, where the authors compare the modeling results to Sentinel-1 timeseries data at a few locations. Unfortunately this section is underdeveloped and the authors miss an opportunity to address some of the open questions regarding Sentinel-1 snow measurements. For example, Lievens et al. (2019, 2022) already showed that the cross polarization ratio is correlated with snow depth when snow depth is greater than ~1.5-2 m, and more recently Hoppinen et al. (2024) showed in greater detail that this relationship breaks down in snow depths below 1.5 m. This presents several interesting questions as to why Sentinel-1 backscatter might be uncorrelated with snow depth in shallower snow - could the authors use their modeling setup to explore this further? Even if this is not possible (e.g. because of a lack of in situ measurements which the authors acknowledge), the analysis and results here need to be expanded for a more impactful contribution. For example, Figures 11-14 visually compare Sentinel-1 and modeled backscatter but there is no attempt to quantify these results, or to relate them back to the snow conditions at the study locations. Expanding the snow-related analysis would help address important open questions in snow radar remote sensing and make this manuscript more impactful to the broader snow community.

Specific comments

Line 31-32: Please provide additional clarification – why is open ground vs vegetation an issue?

Line 35-36: “as there were not enough active snow measurements” – vague

Line 47: “these recent airborne missions” but TerraSAR-X is a satellite platform.

Line 49: Can you briefly provide relevant details of the TSMM platform in the context of the previous discussion in this paragraph? E.g. what sensors/frequencies will be included? Will snow measurements be derived from a backscatter or phase-based approach? Both?

Line 50-69: Please revisit this paragraph and revise with respect to informal and/or redundant language.

Line 52: Lievens et al. (2019) (and the follow-on in 2022) attempt to measure snow depth using Sentinel-1, not SWE as currently stated. This is an important distinction that must be addressed as it brings additional confusion throughout the paper (see comments below).

Line 55: Please provide reference/explanation for 1 meter depth threshold. Is it that higher frequencies are less accurate in deep snow or C-band is less accurate in shallow snow? Perhaps both?

Line 76-77: Please provide a reference if available.

Line 79: Please provide a reference for “sticky sphere model”

Line 85: “As we are dealing with very deep snow” – unclear

Line 87: “can explain the strong cross-pol” – maybe cross-pol response? Or signal?

Line 98-104: Much of this paragraph seems like repeat information from the previous one, including one sentence that is repeated exactly. Perhaps a leftover paragraph from a previous draft? Please revisit and edit/incorporate as appropriate.

Line 106: “the physical model” – please be more specific here. Is this in reference to the bi-continuous DMRT model?

Line 106-115: There seems to be a lot of detailed information here that is not very relevant to the current study. Just a suggestion, but condensing this section may help the reader focus on the details of the numerical methods/models actually used in this study.

Section 2 (Lines 135-156): Imprecise language contributes to additional confusion here. Line 100 states “Cross-polarization observations are used in this paper because they are the basis of snow depth retrieval at C-band (Lievens et al. (2019))” but the figures in this section compare backscatter to SWE. The text in lines 148-150 go on to describe backscatter response to increased snow depth in the figures, even though snow depth is not shown (only SWE).

Lines 138-139: Since Hoppinen et al. (2024) encountered issues reproducing the data processing steps described by Lievens et al. (2022) I strongly suggest a more detailed description of the backscatter data processing. At minimum please include (preferably in an appendix) a description of the software/code used, the original data source, and the specific processing steps. Even better would be releasing the processed backscatter data. I do not see any mention of the processed data in the Data Availability statement.

Line 140-141: Why is the incidence angle important for this study?

Figures 1-3: These are used for essentially illustrative purposes here. I suggest using only one figure here, either from one representative site (put the other two in an appendix if you want) or combine the three sites in one figure somehow.

Line 153-155: Minimizing spatial variability is a reasonable motivation for using Sentinel-1 data at 100 m resolution but how do you square this choice with the following discussion from Lievens et al. (2022, pp 170-171):

> **“The lower accuracy for the [100 m] retrievals can be caused by the larger impacts of (i) radar speckle that is inherent to radar measurements; (ii) geolocation errors and geometric distortions (foreshortening, layover) in the radar images causing location mismatches in γ^0 time series; and (iii) local heterogeneity in topography (elevation, slope, aspect), land surface properties (land cover, soil moisture, soil temperature, and surface roughness), and snow variables (stratigraphy and microstructure).”**

Several of those factors seem like they would be very important to minimize in this study, especially if these effects are inherent in the validation data but not represented in the model chain. Did you try using the 500 m or 1 km data as in Lievens et al. (2022)?

Figure 4: This looks to be an exact reprint of Figure 1 in Tsang et al. (2022). At a minimum that reference to that paper should be included in the caption.

Line 178: C-band is sensitive to snow in the cross-pol but not in co-pol (instead of snow being sensitive to the backscatter as currently written)

Figure 5: This looks to be an exact reprint of Figure 2 in Zhu et al. (2023). At a minimum that reference to that paper should be included in the caption.

Equation 2: Variable N is not defined.

Section 3.1 and 3.2: A high level of modeling background is assumed in this section. I think there is an opportunity here to modify this text so that people with backgrounds in snow hydrology, different snow remote sensing techniques, etc. can better appreciate the importance of this work. Examples (non-exhaustive) of terms that could use references and/or definitions include discrete dipole approximation (line 201), full-wave simulations (203), scattered far fields (208), realizations averaging (208), eigen-quadrature approach (217) sparse matrix canonical grid (228), near field preconditioning (229), Poggio–Miller–Chang–Harrington–Wu (PMCHW) formulation (234), Rao–Wilton–Glisson (RWG) basis function (238), Galerkin's method (239).

Line 202-203: Remove redundant "Step 1 consists of a generation of volume bi-continuous media."

Line 203: Just use the DDA acronym since it was defined in the previous sentence.

Line 205-206: Move the description of the third step after all discussion of the second step.

Line 238: "The L and K operators are defined in Liao et al. (2016)." It would be helpful to briefly describe them here also.

Equations 5 and 6: In addition to L and K, many terms from this equation are not defined.

Line 242: GMRES acronym not defined.

Line 249-262: The phrasing in this discussion is sometimes too informal and obscures the meaning. E.g. Line 255 "This makes cross-pol more sensitive to the snow depth as volume scattering in cross-pol is dominant."

Line 249: Suggestion: Insert a new section title before this paragraph, e.g. "3.3 Forward Modelling Results"

Line 253: Avoid using phrases like "very high" – 200 cm could be considered shallow or moderate snow depth in some places. In fact you imply this in Line 261. Please check for the phrase throughout the document – there are other instances elsewhere in this paragraph and the captions for Table 1 and Figure 8.

Table 1: Consider removing completely. It seems unnecessary alongside Figure 8.

Figure 8: This looks to be an exact reprint of Figure 11 in Zhu et al. (2023). At a minimum that reference to that paper should be included in the caption.

Section 4: The goal/approach of this section is not immediately clear because there is no introduction or transition from the previous section. After reading below and looking at some figures I can understand that the model was run and compared to Sentinel-1 data, but this should be made explicit as the focus of the section from the beginning.

Lines 264-278: Again the framing of the discussion in terms of snow depth does not match the SWE presented in Figure 9.

Line 271 and 277: "little bit of" → "small"

Line 291-292: "The soil moisture (soil permittivity) is decreased as the winter onsets." Please clarify – was this parameter adjusted in the DMRT model until the results matched the S1 data, or did you use some other empirical/physical model for decreasing soil moisture?

Figures 11-14 would benefit from including the snow depth timeseries as well, to provide context for the timing of the Sentinel-1 measured backscatter.

Figures 12-14 should be combined into one longer timeseries figure for easier comparison between the seasons at the same location.

Line 312-314: "As indicated in Section 3 and Lievens et al. (2019), cross-pol signal have small variations for snowpack with depth below 0.5 m. Thus, C-band radar is applicable for the detection of snow with depth above 1 m." What about snow depths between 0.5-1 m? Also, this sentence has been copied almost verbatim from Zhu et al. (2023, p. 3618).

Technical corrections

Throughout document: Check formatting of in-text citations for extra parentheses, e.g. (Kelly et al. (2003)) in Line 25.

Lines 14-15: Suggestion: define the abbreviations "co-pol" and "cross-pol" after the full terms co-polarized and cross-polarized in Line 2. Also check entire document for constancy: "cross-pol" in line 15 vs "cross pol" (no dash) in line 17.

Line 23: Delete "etc"

Line 40: Delete "also"

Line 41: Delete "big" and consider moving this sentence to be the second sentence of the paragraph.

Line 51: Delete "the study of"

Line 79: Acronym QCA is never defined.

Line 129-130: “and the trend that the data are described” – missing a word?

Line 131: “time series data of Sentinel-1 the one season” – unclear

Line 151-152: “was tried to answered” – typo

Line 162: “In 1” → “In (1)”

Line 180: “which in shown by.” – unclear/typo

Line 199: Should be Figure 6.

Line 201: “discreet” – typo

Line 207: “discreetized” – typo

Line 219: “raio” – typo

Line 261: constantly → consistently, change 2 m to 200 cm to match the previous presentation

References

Hoppinen, Z., Palomaki, R. T., Brencher, G., Dunmire, D., Gagliano, E., Marziliano, A., Tarricone, J., and Marshall, H.-P.: Evaluating Snow Depth Retrievals from Sentinel-1 Volume Scattering over NASA SnowEx Sites, EGUsphere [preprint], 1–35, https://doi.org/10.5194/egusphere-2024-1018, 2024.

Lievens, H., Demuzere, M., Marshall, H.-P., Reichle, R. H., Brucker, L., Brangers, I., de Rosnay, P., Dumont, M., Girotto, M., Immerzeel, W. W., Jonas, T., Kim, E. J., Koch, I., Marty, C., Saloranta, T., Schöber, J., and De Lannoy, G. J. M.: Snow depth variability in the Northern Hemisphere mountains observed from space, Nature Communications, 10, 1–12, https://doi.org/10.1038/s41467-019-12566-y, 2019.

Tsang, L., Durand, M., Derksen, C., Barros, A. P., Kang, D.-H., Lievens, H., Marshall, H.-P., Zhu, J., Johnson, J., King, J., Lemmetyinen, J., Sandells, M., Rutter, N., Siqueira, P., Nolin, A., Osmanoglu, B., Vuyovich, C., Kim, E., Taylor, D., Merkouriadi, I., Brucker, L., Navari, M., Dumont, M., Kelly, R., Kim, R. S., Liao, T.-H., Borah, F., and Xu, X.: Review article: Global monitoring of snow water equivalent using high-frequency radar remote sensing, The Cryosphere, 16, 3531–3573, https://doi.org/10.5194/tc-16-3531-2022, 2022.

Zhu, J., Tsang, L., and Xu, X.: Modeling of Scattering by Dense Random Media Consisting of Particle Clusters With DMRT Bicontinuous, IEEE Transactions on Antennas and Propagation, 71, 3611–3619, https://doi.org/10.1109/TAP.2023.3240562, 2023.