Response to Reviewer 2

Dear Reviewer 2,

We thank you for your thorough and very detailed review. We believe your suggestions have led to a more vernacularly accurate manuscript with more thorough descriptions of the radar methods. Specifically, we have added more detailed information about coherence and how it is calculated, we have added reasons for our methodological choices, and we evaluated the Leinss et al. (2015) approximation for ΔSWE retrievals with the 16–22 March 2021 HH InSAR pair. Detailed commentary is provided below in blue. Thank you so much for the time you took to provide your perspective on our work.

Sincerely,
Randall Bonnell, on behalf of co-authors

Review

General Comment

The article ‚Evaluating L-band InSAR Snow Water Equivalent Retrievals with Repeat Ground-Penetrating Radar and Terrestrial Lidar Surveys in Northern Colorado' compares SWE change retrievals from airborne interferometric SAR data, ground penetrating radar, terrestrial lidar scans, automated measurement stations and in-situ measurements. The paper provides an extensive data analysis for two winters (2020 and 2021) over different test sites in Colorado. The authors also analyze the impact of low coherence on the SWE change retrieval, providing valuable insights for future space borne L-band SAR missions.

Specific Comments

Line 37: Maybe you can add half a sentence why the agreement was poor in 2020.

Thank you for this suggestion. We feel that the statement is not representative of our results. For example, if you select any three consecutive InSAR pairs from 2021 in Figure 10, you may see poor agreement. We have revised this sentence to read, "UAVSAR ΔSWE showed some scatter with ΔSWE measured at automated stations for both study years, but cumulative UAVSAR SWE yielded a r = 0.92 and RMSE = 42 mm when compared to toal SWE measured by the stations."

Line 98: The meaning of this sentence is hard to understand. Maybe you could rephrase it.

Thank you for this suggestion, the sentence has been revised to state the cause of atmospheric delays and to correct a typo: "...only two of these studies have not considered atmospheric signal delays…" to "only three of these studies have considered atmospheric delays.

Line 100-108: You could think of adding this paragraph about the interferometric coherence to Appendix A.2., where you also describe the interferometric phase.

The purpose of this paragraph is to provide a high-level summary of coherence as an InSAR parameter and review the recent studies that have analyzed its influence upon SWE retrieval accuracy. We have decided to leave the paragraph as is, but have added more detailed information about coherence in Appendix A.2.

Line 124: Why have you used a different heading for the 27.01. /03.02. interferogram and not the 141° as well?

At the time of data analysis, the 141° heading for 27 January to 3 February 2021 was not available because of a >70 m deviation from the spatial baseline. We are aware that a product has since been calculated, but because of this significant baseline deviation, we are hesitant to incorporate it into our analysis and prefer the 321° pair because of its significantly tighter spatial baseline.

Line 177: Do you know why the coherence was low for that interferogram? Please elaborate briefly.

We are uncertain about the exact cause of the low coherence for the 10–16 March interferogram. Between those dates, a significant snow storm deposited ~70 mm of SWE, as measured by the nearby Joe Wright SNOTEL station, which is expected to reduce coherence. Another possibility is the development of ice lenses in the snowpack (noted in Section 4.1), which would alter the backscattering properties between acquisitions. A final and likely possibility is that the >3 m deviation from the spatial baseline between the two acquisitions yielded phase changes that were unaccounted for in the topographic phase correction performed by UAVSAR.

Line 183: Maybe you can point out that it is a SWE change retrieval, so you can just measure changes between the measurements, and not directly the total SWE.

Thank you for this suggestion. We have added the clarification.

Line 211: Were the 20% GPR SWE change retrievals used for estimating the absolute phase selected randomly? And why have you not used the In-Situ stations for absolute phase calibration?

Yes, the phase calibration was performed using a randomly selected set of 20% of the GPR ΔSWE Retrievals. We have added this statement to Line 211 for clarification.

We opted to use the GPR ΔSWE retrievals for phase calibration instead of weather stations for a two primary reasons:

1. Coherence at weather stations was often <0.4 (Figure 10), whereas the coherence distribution along the GPR transects was centered on ~0.65 (Figure 8a). Although we show that there is not much variability in InSAR ΔSWE error based on coherence, we did not know this going into the study and wanted to optimize the phase calibration using the measurements that had higher coherence.
2. Even for the dates where <200 UAVSAR pixels had coincident GPR measurements, we still had >25 GPR measurements to derive a statistical phase calibration. We found this to be a favorable statistical approach as compared to the, at most, seven automated stations.

Line 271: What is the resolution your 3x3 pixel grid?

The UAVSAR pixels have a spatial resolution of ~5 m x ~5 m, therefore the resolution of the 3x3 grid is ~15 m x ~15 m. We have added this to the text.

Line 352: Why have you chosen HH and not VV? Since the RMSE is smaller for VV.

Previous studies have noted that retrievals are valid from any of the polarizations, but co-polarized datasets are preferred because of the stronger strength of the backscattered signal (e.g., Palomaki & Sproles, 2023). Therefore, we aimed to present a time series from either HH or VV. Of the polarization time series, the HH polarization is only missing data from the 3–23 February 2021 InSAR pair, whereas VV is missing data from both the 12–19 February 2020 and the 3–23 February 2021 InSAR pairs. Thus, it is our opinion that the time series from the HH polarization is the easiest of the two to explain. As we state in Section 4.3, overall RMSEs are similar between all four polarizations and we do not think the 2 mm difference in overall RMSE warrants the use of a different polarization.

Line 492: In this paragraph you are discussing the influence of wet snow. Maybe you can also add that wet snow increases the absorption and decreases the penetration depth of the radar wave in the snow volume.

Thank you for this note. We have added a sentence about the effects of liquid water content upon the radar signal and described the uncertainty of the location of the amplitude-center at higher water contents.

Line 520: In your Appendix A.1 you describe the L-Band transmissibility, which is very interesting, but you never refer to A.1.

We have added a line to the introduction (Line 81) to point readers to Appendix A.1 for a review of the transmissibility of L-band radar through snow.

Line 538: (Referring to comment on line 100-108). Maybe you could also add here an equation for the interferometric coherence, so it is easier to understand what it means and how you can obtain the interferometric phase.

Thank you for this note. We agree that the appendix is a sensible location for the coherence equation, particularly since the phase unwrapping method relies upon it. The equation and a brief explanation have been added to Appendix A.2.

Line 548: In A.2.2 you are describing the atmospheric correction for UAVSAR. I am not an expert in this field, but I understood that you are estimating a phase ramp due to the atmosphere and then are checking if the atmospheric correction is improving your SWE change estimates. You stated that it does not improve your results. But where does your calculated phase ramp then come from? Maybe you could explain this more.

We appreciate your discussion of this topic. The calculated phase ramp is the result of a linear regression between the radar signal path length (i.e., distance between the SAR and the ground reflector) and the unwrapped phase of pixels that were identified as snow-free through the Normalized Difference Snow Index Analysis. The regression equation is then applied to the unwrapped interferograms to account for the atmospheric contribution to the phase delay. However, as we note in Appendix A.2.2, the estimated atmospheric corrections were generally poor and did not improve the ΔSWE retrieval accuracy compared to the automated stations.

Line 595: In (Leinss et al., 2015) an approach was presented, where a linear function between the SWE change and interferometric phase was derived. This has the advantage that you can directly derive the SWE change from the phase without the need of additional in-situ density measurements, which is the main advantage of the DInSAR approach compared to the GPR or LIDAR retrieval. Maybe you can think about it, since you also stated in line 66 that the need of in-situ density measurements adds uncertainty. Or state why you have chosen to use the approach with Equation (A5) and (A6).

Yes, we absolutely agree that the linear approximation, which is independent of density, is a primary factor that makes the L-band InSAR method for global SWE retrievals promising! We designed our scripts to use the density-dependent method because surface density was set as a target observation during the surveys and we were unsure whether liquid water content was within the snowpack during UAVSAR flights in March of 2020 and 2021. The Leinss et al. (2015) approximation was developed exclusively for dry snow applications as defined by the dry snow permittivity model that was used in their linear approximation. As we conclude in our manuscript, it is unlikely that liquid water was present at our field sites during UAVSAR flights, hence the Leinss et al. (2015) approximation may be appropriate for our analysis. However, incorporating the approximation at this stage instead of the density-dependent method that we used would require extensive changes to statistics and methods throughout the manuscript for what may result in a nearly identical evaluation. Thus, we opted to retain our focus on the density-dependent method, which is an appropriate and accurate approach, particularly given that the method is relatively insensitive to the input density (Hoppinen et al., 2024). Additionally, there is precedent for the density-dependent method to be used for airborne platforms, which tend to have a larger range of incidence angles than satellite platforms, making the Leinss et al. (2015) approximation a bit more uncertain. For reference, recent airborne L-band InSAR studies that have used the density-dependent method include Hoppinen et al. (2024), Marshall et al. (2021), Nagler et al. (2022), and Tarricone et al. (2023).

We decided to test the Leinss et al. (2015) approximation using the 16–22 March 2021 HH InSAR pair to determine its appropriateness for the UAVSAR platform (see figure below). Scene-wide ΔSWE retrievals are identical between the density-dependent method that we implemented in the study and the Leinss et al. (2015) approximation ($r = 0.99$; Figure a–c). When evaluated using the GPR ΔSWE retrievals, both methods yield identical Pearson's correlation coefficients and RMSEs (Figure d–f). We have added the analysis and methods of this evaluation to Appendix 2 and the figure has been added to the supplement. We conclude that, for dry snow, the Leinss et al. (2015) method is applicable from airborne platforms.

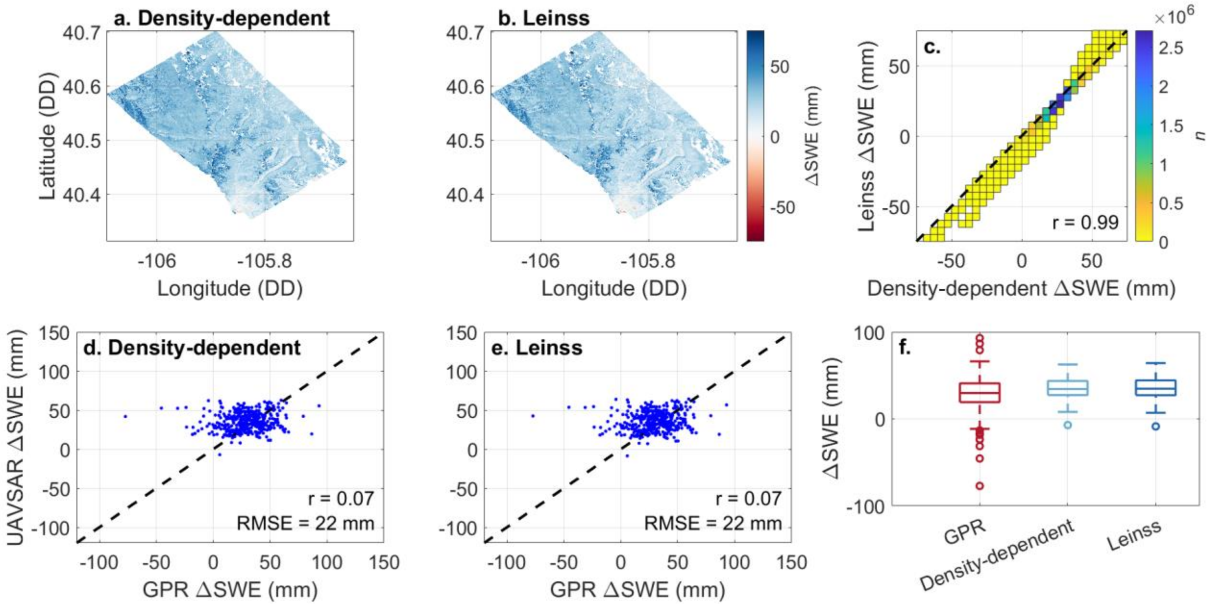

Figure: Evaluation of the Leinss et al. (2015) approximation for ΔSWE retrievals from the 16–22 March 2021 HH InSAR pair. ΔSWE retrievals calculated from (a) the density-dependent equation used in the manuscript and (b) the Leinss et al. (2015) approximation. (c) Comparison between the density-dependent and Leinss et al. (2015) approximation ΔSWE retrievals. Comparison of GPR ΔSWE retrievals with (d) the density-dependent method and (e) the Leinss et al. (2015) approximation. (f) Box plot distributions of ΔSWE retrievals from the three methods. For plots a–c, the range of ΔSWE is limited to ±75 mm, which represents >99% of the distribution.

Line 598: You maybe could point out that these are snow depth changes and SWE changes.

Accepted.

Technical Corrections

Line 53: Reference for the SNOTEL stations

Accepted.

Line 183: ...is outlined in Appendix A.2?

Agreed. Thank you for this suggestion.

Line 236: The GPR Workflow in Figure 2 shows the Radargram processing and it has first the step (4) and then the step (3). Maybe you can make it more consistent.

You are correct in your assertion, the trace interpolation step is performed before the 2-d filter step. Thank you for catching this typo. The GPR workflow figure has been changed to accurately reflect the processing flow.

Line 320, Line 333: It is hard to see the points in Figure 5 (i) and Figure 6 (i).

Unfortunately, phase unwrapping issues for the 3–23 February 2021 InSAR pair removed any potential evaluation at the MR field site, hence Figure 5i does not have any GPR points visible. We have added a sentence explaining this to the figure caption.

I assume that this is a reference to Figure 6f, rather than Figure 6i. This subplot represents the 3–23 February 2021 InSAR pair at the CP field site. For this interval, ΔSWE was large and maximized the color scheme, hence the difficulty identifying the GPR points. We have changed the outline of the GPR points to improve the contrast.

Line 352: Space after Figure missing.

Addressed. Thank you for catching this typo.

Line 352: Parenthesis after HH.

We believe this issue has been addressed in our response to your comment for line 353.

Line 353: In the Table S4 the RMSE is 21mm and not 22mm.

We appreciate your eye for detail. The overall RMSE for the HH polarization is 21 mm. However, as shown in Table S4, this does not include any SWE retrievals from the 3–23 February 2021 InSAR pair. We have added a sentence to Section 4.3 that specifies that, for the presented analysis, we used the HH pol for all pairs except the 3–23 February 2021 which used the VH pol. We have also added a sentence in the description for Table S4 that describes the differences between the overall statistics reported in the table and the overall statistics reported in the manuscript. We hope that this clears up the confusion.

Line 375, Line 378, Line 382: There is no Figure 8 (a-i).

Thank you for catching this mistake. The figure references have been updated to reference Figure 9 (a–i).

Supplementary Material:

Line 62: There is only Figure 8 (a-b).

Thank you for catching this. It has been corrected.

References

Hoppinen, Z. M., Oveisgharan, S., Marshall, H.-P., Mower, R., Elder, K., and Vuyovich, C.: Snow Water Equivalent Retrieval Over Idaho, Part 1: Using L-band UAVSAR Repeat-Pass Interferometry, The Cryosphere, 18, 575-592, https://doi.org/10.5194/tc-18-575-2024, 2024.

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Nagler, T., Rott, H., Scheiblauer, S., Libert, L., Mölg, N., Horn, R., Fischer, J., Keller, M., Moreira, A., and Kubanek, J.: Airborne Experiment on Insar Snow Mass Retrieval in Alpine Environment, in: IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium, IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium, 4549–4552, https://doi.org/10.1109/IGARSS46834.2022.9883809, 2022.

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