Response to Reviewer 1

Dear Dr. Jeff Dozier,

Thank you for your thorough review of our manuscript. We found your suggestions to be helpful and we believe your commentary has led to an improved manuscript. Specifically, we have improved the accessibility of the manuscript, reorganized and added sections for radar methodology, explored a ΔSWE retrieval method independent of density (Leinss et al., 2015), and evaluated the accuracy of the Copernicus-derived incidence angles. We addressed the manuscript's accessibility by including definitions and descriptions for many of the complex terminology and referring readers to previous studies that include sketches and more detailed descriptions of the methodology. We have added sentences to the introduction and to the appendix to improve our explanations of phase and coherence. Finally, two sections were added to the appendix to include the evaluation of ΔSWE retrieval uncertainty caused by Copernicus-derived incidence angles and a study on the Leinss et al. (2015) ΔSWE retrieval methodology. Below, you will find our responses to your review in blue. Thank you for the time you put into writing such an insightful review.

Sincerely,

Randall Bonnell, on behalf of co-authors

This paper presents interesting results that offer both hope and caution for L-band InSAR and InSAR generally. The quality and extent of the field validation data are impressive, perhaps the best I've seen from a field snow experiment.

Three suggestions to improve the analysis and the presentation:

1. My major critique is that the target audience has to know a lot about radar and radar remote sensing of snow properties to understand the paper's implications. Craig Bohren has a pointed phrase about a subject being "well known to those that know it well," and this paper unfortunately hits that spot especially in the Introduction. Some colleagues tell me that the coded vocabulary makes the radar remote sensing literature hard to penetrate.

Thank you for your candor. We feel that our edits have made this a more approachable paper without becoming too much of a review. In summary, we have added more details for radar terminology and radar wavelengths/frequencies and we added an equation for coherence to the Appendix. Further details are provided for each of your comments below.

2. The approach for all the methods for SWE retrieval seems to combine a measurement of depth by some remotely sensed method, and then to multiply those depths by estimates of density. With snow depths retrieved from lidar or photogrammetry, this is the viable approach, but from InSAR data it's feasible (and probably better) to directly retrieve SWE without estimating depth or density.

Our approach for ΔSWE retrievals was deliberately chosen because surface density was a target observation during our field campaigns, we wanted our algorithm to be adaptable in case we found evidence for liquid water content, and there has been precedent set in recent years to use the density-dependent equation for airborne platforms (e.g., Hoppinen et al., 2024; Marshall et al., 2021; Nagler et al., 2022; Tarricone et al., 2023). The linear approximation between phase-change and SWE-change is an aspect that makes the InSAR method so appealing for large-scale SWE retrievals. We decided to maintain our focus on the density-dependent equation, but have used the Leinss et al. (2015) approximation to calculate ΔSWE retrievals for the 16–22 March 2021 HH pair for comparison with our ΔSWE retrievals. A summary of our results can be found at the end of this document, and we have added a section to the Appendix to discuss the analysis. We found the Leinss et al. (2015) approximation to be nearly identical to our density-dependent inversion and we plan to use the Leinss et al. (2015) approximation for future InSAR SWE retrieval studies.

3. The explanations for getting SWE from InSAR are scattered throughout: in the Introduction, Section 3 (Methods), or the Appendix. Perhaps consolidating might be the answer, or advise some readers to read the Appendix first.

Our intent was to give a high-level introduction to InSAR for SWE retrievals in Section 1, give a summary of the UAVSAR methods in Section 3.1, and detailed methodology in Appendix A.2. We have added a sentence in the introduction (Line 96) and at the beginning of Section 3.1 to direct readers to the appendix.

Some line-by-line comments, but consider in the context of the three points above.

Line 30: maybe insert a short parenthetical definition of L-band (frequency 1-2 GHz).

We have added your suggestion and have also added the approximate L-band wavelength.

Line 35: I tend to avoid adjectives ("high" here) to describe statistical measures like correlation. In some spectroscopic retrievals I work on, $r<0.9$ is awful. Present the values themselves.

We agree with your point and have adjusted the sentence accordingly.

Line 34: Is “coherence” the same as “correlation”? Without knowing that, some of the rest of the Abstract is hard to interpret. In general, this issue pervades the paper. Coherence is shown to be important but isn’t defined.

Coherence and correlation are often used synonymously for InSAR. For example, the calculation of coherence is described in *Introduction to Microwave Remote Sensing* (Woodhouse, 2017) as using the complex correlation approach for interferometric radiometry. The primary difference is that radar interferometric coherence uses a spatial average whereas interferometric radiometry correlation uses a temporal average. We have specified in the abstract and the introduction that coherence refers to the complex interferometric coherence and have moved the definition of coherence to line 97.

Line 36: poor in one year, good the next. Any explanation? I see on Line 420 that this may be an artifact of mis-registration between airborne and in situ data.

Thank you for this comment. Upon review of the abstract, this sentence is an oversimplification of what we found. Yes, spatial baselines were better aligned in 2021, but poor agreement for several sequences of three InSAR pairs is observed in Figure 10a–g. For example the sequence of 2021 InSAR pairs for 15–20 January, 20–27 January, and 27 January to 3 February yielded poor agreement with the SNOTEL SWE.

We have revised this sentence to more accurately describe our results: “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 total SWE measured by the stations.”

Line 37: The sentence “We found that …” seems incongruous with RMSE between 19-22 mm. It would also be useful to specify the ranges of SWE (total) and ΔSWE (between passes) in the experiment. This information does show up later in the paper.

We agree and have revised this sentence to read: “Further, UAVSAR ΔSWE RMSE ranged by <10 mm from coherences of 0.10 to 0.90, suggesting that coherence has only a small influence on the ΔSWE retrieval accuracy.”

We have revised lines 30–31 to state the approximate SWE accumulation that occurred during the UAVSAR campaigns.

Line 47: The Wrzesien 2018 paper covered North America but the sentence is global. Maybe cite the 2019 paper instead (DO10.1029/2019WR025350I) or clarify that the sentence applies to North America in the 2018 paper.

Thank you for catching this. We have updated the citation to Wrzesien et al. (2019)

Line 54: SNOTEL stations are all on nearly flat terrain, hence interpolating between them misses effects of slope and orientation. This sampling bias, combined with the spatial and elevational extent of the snow pillow network, subjects interpolation to artifacts.

Thank you for this suggestion. We have specified that the spatial variability of snow, coupled with the location bias and limited elevational extent of automated stations, limits interpolation.

Line 56, let's correct a misunderstanding: National Academies of Sciences, Engineering and Medicine are NOT a "government agency."

Thank you for this clarification. We have specified that snowpack monitoring via remote sensing has been set as a high priority by the National Academies of Sciences, Engineering, and Medicine.

Line 60: I don't think SnowEx was a "mission." The Durand et al. 2018 reference uses "campaign."

Accepted

Line 65: "is" not "are".

Accepted. Thank you for catching this.

Line 72: Need a short tutorial here explaining what backscatter, time-of-flight, and co-polar phase difference are. And then a sentence about why the paper focuses on InSAR (which indeed is defensible). The reference to Borah et al. 2023 perhaps distracts. If indeed we can measure SWE up to 800 mm based on backscattering at X- and Ku-band, why go to interferometry? Earlier work by Jiancheng Shi also got impressive results based on multifrequency multipolarization backscatter, albeit with validation by a only few snow pits.

Consider this comment in the context of data processing. Then the details of how you measure coherence, time delay, phase angle, etc. (now Lines 85-107) can be covered in Section 3 or in the Appendix (but make the forward reference).

Thank you for the constructive feedback! We have provided brief explanations of SAR backscatter physics (line 75) and what time-of-flight means in the context of radar (line 72). We mention co-polar phase difference for completeness, and thus have directed readers to Leinss et al. (2014) and Patil et al. (2020).

Regarding SAR backscatter methods, we have adjusted the reference to Borah et al. (2023) to read, "...with the potential for retrieving SWE in deeper snowpacks (Borah et al., 2023)." We have added a line regarding the snow depth retrievals from backscatter methods of Shi and Dozier (2000). Finally, we emphasized the advantage of InSAR for SWE retrievals, particularly the linear approximation between changes in SWE and phase change.

Line 74 et seq. At the first introduction of “frequency,” it would be useful to include a short table that translates between “Q”-band, frequency, and wavelength. I hope that this paper will be read by people who have no idea what X-band is, or whether X-band’s frequency is greater than or less than P-band’s.

Thank you for this suggestion. We agree that radar vernacular can be a significant barrier for readers and it would be quite unfortunate for a reader to give up on our paper because of an accessibility issue. We have added frequency ranges and approximate wavelengths to all first mentions of radar bands.

Line 85: Maybe a sketch here to explain what a phase change and a coherent reflection are, or cite where one can find an explanation, or refer to Section 3 or the Appendix. In the current version, it’s difficult to figure out how one goes from measurement to estimate of phase change.

We have added a referral to Appendix A.2. Additionally, Guneriussen et al. (2001) was provided as a citation and has a complete review of the method along with sketches that illustrate how the phase change is used to estimate a change in SWE. Thus, we feel that including a sketch here would be somewhat redundant and out of the scope of our paper.

Line 86: “The technique was first established at C-band . . .” First established to do what? Does this remark refer especially to snow, or to interferometric retrievals of elevation?

Thank you for catching this. Guneriussen et al. (2001) was the first study to use InSAR to retrieve SWE. We have clarified this sentence.

Line 88: “interferogram” indeed well known to a small community, possibly obtuse to other readers.

We have revised this line to include the definition of interferograms.

Line 98: Not sure what “only two of these studies have not considered atmospheric signal delays” means. Does it imply that signal delays are important, but seemingly well covered?

We have removed the word, “not”, as this was a typo. We have also corrected “two of these studies” to “three of these studies”, which includes Hoppinen et al. (2024), Oveisgharan et al. (2024), and Tarricone et al. (2023). We have also added text in line 99 to describe the cause of atmospheric delays.

Line 100-108: This paragraph has information, but not enough to know how one gets a measurement of phase difference between an interferometric pair. Also, is coherence the same as a product-moment correlation? Or something related but different?

The purpose of this paragraph is to frame coherence as a parameter that may be necessary for robust InSAR ΔSWE retrievals, but few evaluations on coherence have been published with respect to ΔSWE retrieval accuracy.

A phase-change can be calculated from any two waveforms, but a phase-change is only meaningful if the two waveforms are sufficiently coherent. Thus, coherence is a measure of similarity between two waveforms and it is different from product-moment correlation.

We have pointed readers in line 82 to Appendix A.2, where we have added a sentence that includes the equation for coherence and a description for how coherence is used for InSAR.

Line 170: I suggest expanding section 3.1 with material from the Introduction (line 85-107) For the less informed reader, the relationship between coherence and phase is arcane. In particular, the snow properties that degrade coherence are important and affect the need for frequent image acquisition. How is the interferometric phase angle determined from the correlated (cohered?) pairs?

We have added a sentence to Section 3.1 that describes phase and phase cycles and we have added information to Appendix A.2 that describes how coherence is used for InSAR applications. We feel that the material in the introduction regarding coherence degradation and the need for frequent image acquisition is appropriately placed.

Line 177: And then we have to worry about "phase unwrapping," but this text doesn't tell us what that is. Also, is phase unwrapping a problem generally with SAR at L-band and higher frequency? Perhaps interpret the equations in Leinss et al. 2015 to explain? (Later I see phase unwrapping at ~100 mm)

We have revised Section 3.1 to include a description of phase cycles and unwrapping.

Admittedly, phase unwrapping is less of an issue at L-band than it is for C-band or higher frequencies because the ±π phase cycle (~±108 mm ΔSWE for UAVSAR) expands with increasing wavelength. However, phase unwrapping is dependent on coherence. As mentioned previously, we have added a sentence that discusses phase unwrapping and coherence in Appendix A.2.

Figure 2 and Line 196: Calculations of Incidence Angles from the Copernicus DEM lead to an uncertainty in cosine(incidence) of ~0.1 (from my own work, DOI 10.1029/2022JG007147), but are you able to overcome this problem because repeated images get you the right incidence geometry? Otherwise this is a source of uncertainty, even with the best available global DEM.

Thank you for this comment. UAVSAR provides a look vector data product that includes the spatially distributed east, north, and up components of the radar signal path. This look vector is calculated as the average for the flight path and is used in conjunction with the DEM to calculate incidence angles (Appendix A.2).

We took this comment as an opportunity to better understand the uncertainty here. Two lidar flights were flown over a portion of the UAVSAR swath and both field sites in 2021. From these flights, digital elevation models have been made publicly available (Adebisi et al., 2022). We evaluated incidence angles derived from the Copernicus DEM with incidence angles derived from the lidar DEM and then ran a Monte Carlo simulation using 100,000 realizations to better understand the ΔSWE error associated with the Copernicus DEM. We found that the Copernicus and lidar incidence angles yielded similar spatial patterns, but the Copernicus-derived incidence angles failed to resolve many of the fine scale features observed in the lidar-derived incidence angles (Figure S2a–b). Overall, the two sets of incidence angles yield a low Pearson's correlation coefficient (r =0.08), but the distribution is centered on the one-to-one line. Using the calculated RMSE of 20°, a phase change of 0.5π radians, and a surface density of 150 kg m^{-3} within the Monte Carlo simulation, we estimate a ΔSWE uncertainty of ±7 mm from the Copernicus-derived incidence angles.

We have added a statement in Section 3.1 to direct readers to Appendix A.2 for a review of this evaluation.

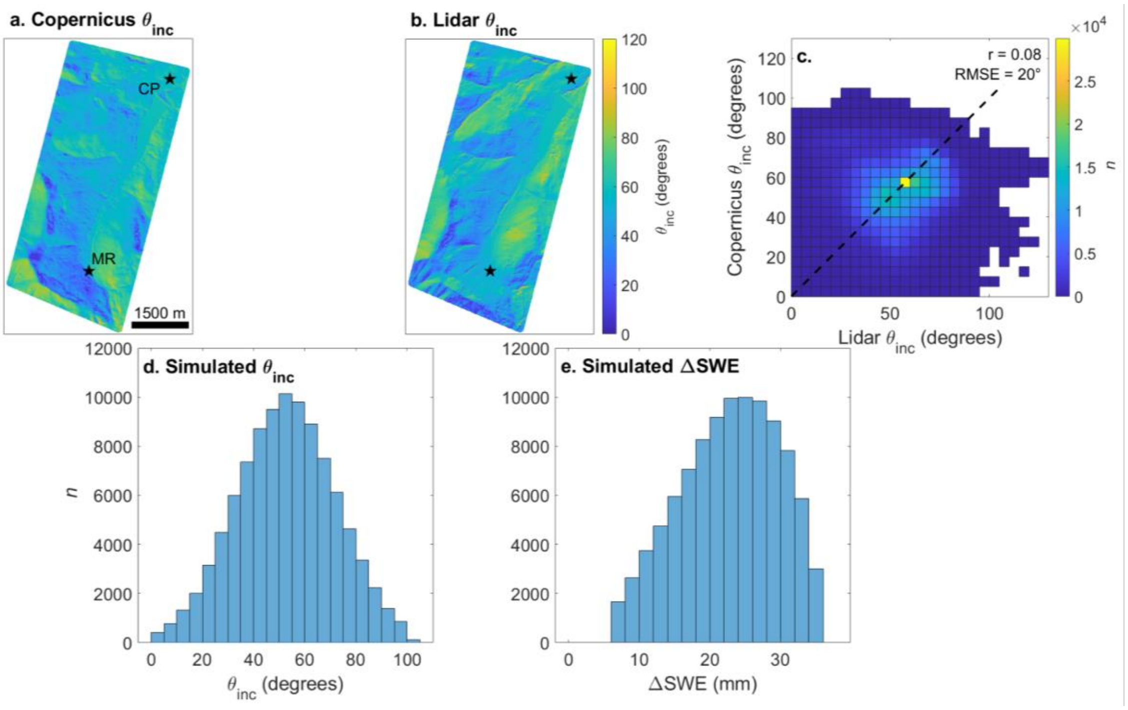


Figure: Incidence angles derived from (a) the Copernicus 30 m DEM and (b) the 0.5 m lidar DEM. (c) Comparison between the Copernicus-derived and the lidar-derived incidence angles. Results from the Monte Carlo simulation of (d) incidence angles and the (e) corresponding ΔSWE. The Monte Carlo simulation was based on a mean incidence angle of 52.8° with a 20° standard deviation, a snow density of 150 kg m^{-3}, and a phase change of 0.5π radians.

Line 215: Can you include an equation that defines Coherence? Or is it just Pearson product-moment correlation?

We have included the coherence equation in Appendix A.2.1.

Line 235: Maybe include a citation to Reflex W? I may not need to know what a "de-wow" filter is, but I'd like to know that I could find out.

Thank you for this suggestion. We added text to describe the de-wow filter as a one-dimensional filter that removes low-frequency noise and a reference to the ReflexW software (Sandmeier, 2019).

Line 248: The title of Section 3.2.3 is "TLS" but the section also covers the UAV lidar.

Yes, the USGS, in coordination with our field efforts, collected and performed all processing on the snow-off UAV-lidar dataset. We have renamed section 3.2.3 "Lidar Scans." We have not adjusted subsequent TLS headings, labels, or phrasings because all snow-on scans were collected from a terrestrial platform.

Line 283: "phase cycle" appears here for the first time. The cognoscenti know what this is but some readers may not.

We have addressed this comment by describing phase cycles and unwrapping in Section 3.1, per the previous comment regarding Line 177.

Line 424: "phase unwrapping" is mentioned here and elsewhere. In processing the interferometric phase values, how do you decide when you've gone through a phase cycle? Or more than one?

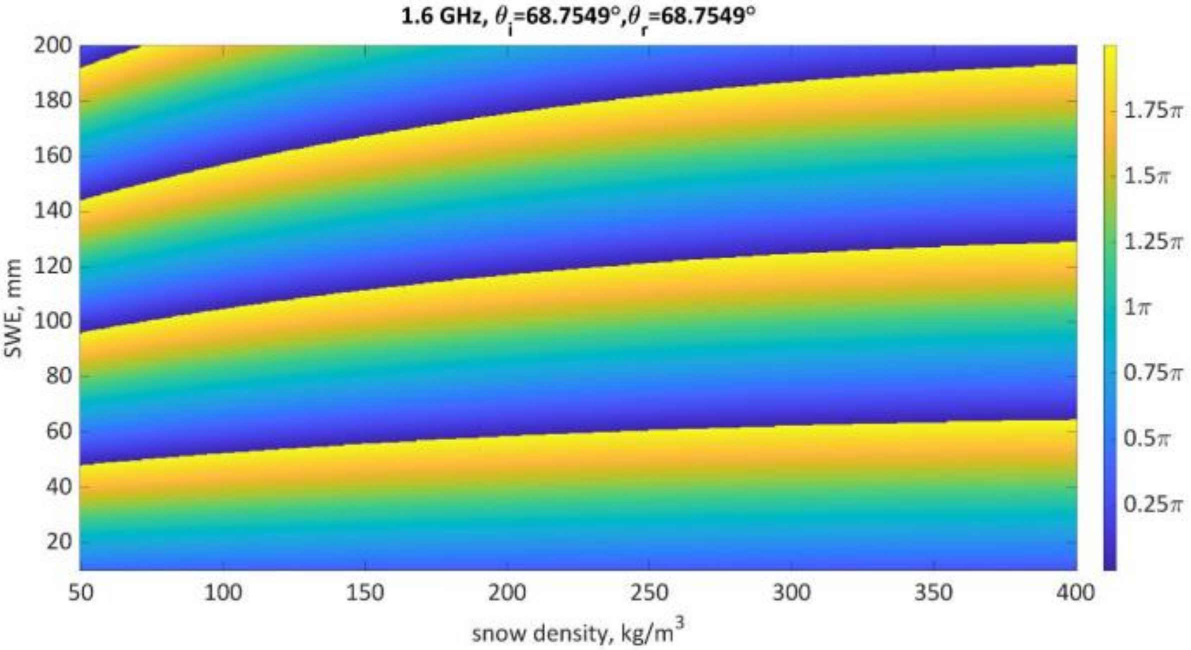
InSAR measures phase deformation within a ±π phase cycle (~±108 mm). For some accumulation events, many pixels within a scene may see a ΔSWE >108 mm, which means that phase unwrapping is necessary to calculate the "true" ΔSWE. In brevity, phase unwrapping integrates the pixel-wise phase differences across the swath to estimate the true phase deformation. In Appendix A.2.1, we cite Goldstein and Werner (1998), the algorithm that UAVSAR implements when their team unwraps interferograms.

ESTIMATING SWE DIRECTLY FROM InSAR (instead of estimating depth and multiplying by density)

Rearrange Eq. (A5) to calculate φ_s (similar to how Leinss et al. 2015 explain):

$$\varphi_s = \frac{4\pi\Delta d_s}{\lambda}\left(-cos\theta_i + \sqrt{\varepsilon_s - sin^2\theta_i}\right)$$

By inspection, two snow terms drive φ_s to increase, ε_s which depends on density ρ_s, and Δd_s. The relationship is nearly linear, certainly linear in Δd_s and nearly linear in ρ_s. ΔSWE = $\Delta d_s \rho_s$, so different combinations of Δd_s and ρ_s can yield the same ΔSWE. ΔSWE = f(φ_s) is nearly linear with a weak dependence on density only at combinations of deep snow with low densities.



Thus, a compelling argument for InSAR is its lack of dependence on density, in contrast to lidar for example where the biggest uncertainty is that in density.

We wholeheartedly agree with your assertion! The ability to retrieve SWE without density makes the L-band InSAR method particularly promising for global SWE monitoring applications. When we began our analysis, we specifically designed our scripts to use the density-dependent method because surface density was set as a target observation during the surveys and we wanted to use an equation that could accommodate any potential liquid water content in the snowpack. Through our analysis, we determined that liquid water content was not likely present in the snowpack at our field sites during the UAVSAR flights.

Although approximations such as the Leinss et al. (2015) equation are the most likely InSAR equations for global SWE retrievals, the density-dependent method we implemented 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 tested 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. However, we have decided to maintain our focus on the density-dependent method because the central findings and implications would likely remain the same, but extensive small changes to figures and statistics throughout the manuscript would be required if we fully adopted the Leinss et al. (2015) approximation.

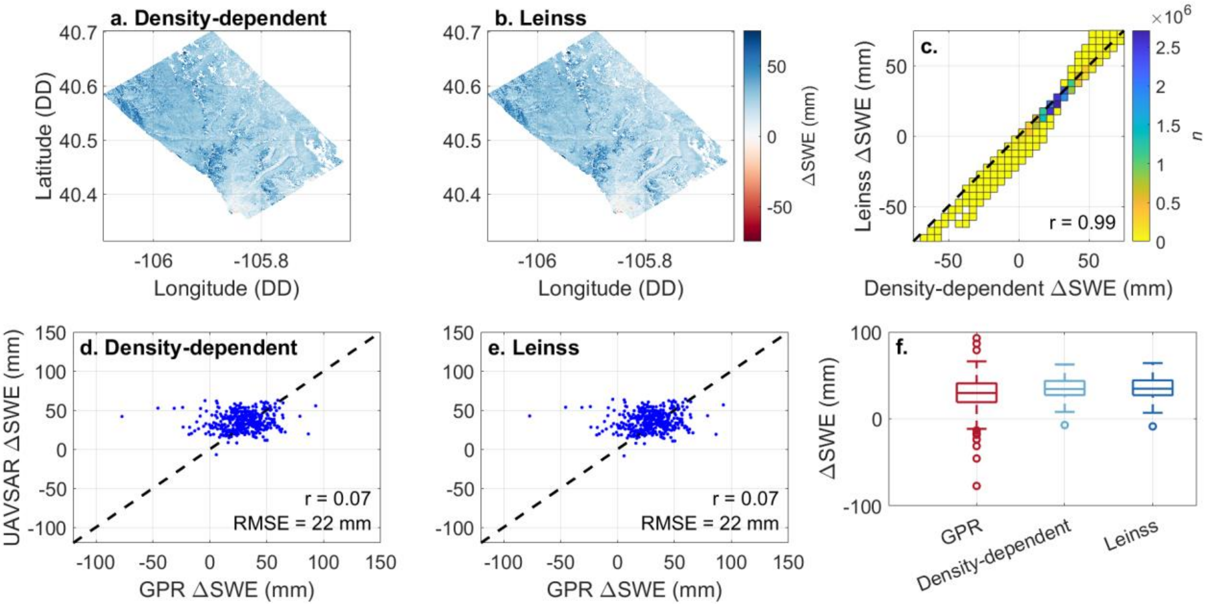


Figure: Evaluation of the Leinss et al. (2015) approximation for ΔSWE retrievals from the 16–22 March 2021 HH InSAR pair. ΔSWE retrievals calculated from (a) the density-dependent equation used in the manuscript and (b) the Leinss et al. (2015) approximation. (c) Comparison between the density-dependent 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.

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