Response to Reviews

Reviewer #1 : Eusang Cho

Thank you for your comprehensive and insightful review of our manuscript. Your comments and suggestions are invaluable in strengthening the study and ensuring the clarity and robustness of our findings. We appreciate the time and effort you have invested in evaluating our work. Our responses follow in red font.

General comments

1 My understanding is that the MS-1000 gamma spectrometer measures gamma count rates of 40K, 238U, 232Th, and 137Cs radionuclides. When the authors apply Eq 2 to calculate SWE, how did they calculate the count rates (c_bare and c_snow) from the individual gamma elements? If the authors used 'total count rates' regardless of radionuclides, can the authors provide the gamma radiation spectra like Figure 12 in Offenbacher and Colbeck (1991)? That would be helpful for potential readers to better understand the passive gamma radiation technique and its attenuation effect by snowpack. I would also suggest providing spatial maps of gamma count rate for each radionuclide along with the total count rates as supplementary.

Offenbacher, E. L. and Colbeck, S. C.: Remote sensing of snow covers using the gamma-ray technique (No. AD-A- 238016/0/XAB; CRREL–91-9), Cold Regions Research and Engineering Lab., Hanover, NH (United States), https://apps.dtic. mil/sti/pdfs/ADA238016.pdf, 1991.

We agree that aligning with some of the existing SWE-gamma work that focuses on the sensitivities associated with different specific radionuclides (like in Offenbacher and Colbeck (1991)) would be useful. We did attempt to implement those approaches early in the project but made the decision to focus on the total count rates, as they were shown to be more robust overall. The MS-1000 unit provides the means to isolate the emissions from specific radionuclides; however, it does this through interpretation/integration of the spectra. In the mobile application described, using high frequency (1 second) integrations of the spectra, we found that there was an unreasonable amount of noise versus signal when looking at the SWE with respect to specific radionuclides. Additionally, it was not possible to perfectly align (spatially) the point scale gamma spectra over snow versus over bare ground. Thus, we felt it more appropriate to utilise the total count rate approach, which has had well documented usage (Carroll, 2001), instead of the specific radionuclide approach. We will add more detailed justification to the manuscript for this approach, along with spatial maps of gamma total count rates as supplementary material as suggested.

Carroll, T.: Airborne Gamma Radiation Snow Survey Program: A User's Guide. Version 5.0, National Operation Hydrologic Remote Sensing Center., 2001.

2 Related to Comment 1.1, it should be clearly articulated why they used total gamma count rates rather than specific radioisotope components such as 40K, which are expected to be more sensitive to better quantify the attenuation by SWE (Peck et al., 1971; Offenbacher & Colbeck 1991). I understand the authors want to avoid the empirical aspects; However, I still think some justifications would be valuable. Specifically, if possible, a simple comparison of the gamma SWE values derived from total gamma counts used here and specific gamma radioelements (e.g., previous studies were used) would be valuable for potential readers.

Peck, E. L., Bissell, V. C., Jones, E. B., & Burge, D. L. (1971). Evaluation of snow water equivalent by airborne measurement of passive terrestrial gamma radiation. Water Resources Research, 7(5), 1151-1159.

You raise an important point about the decision to use total gamma count rates rather than specific radioisotope components. We will provide a clearer justification for this approach inline with the previous comment, incorporating a comparison of gamma SWE values derived from total gamma counts and specific gamma radioelements, as you suggested in the supplement. This comparison will help to contextualize our approach within the broader field of study.

3 Regarding the overestimation of SWE in Grassland in the second winter, I agree with the discussion point (L340-348) that a melt event earlier can contribute to the SWE uncertainty. To further discuss, I think it would be helpful if a time series of soil moisture and SWE throughout the season can be provided (if the station data is available near the sites). In this context, it might also be helpful to include a time series of temperature, snow depth, and precipitation at a GWFO station in the main body or as supplementary material for a better understanding of site weather conditions before and after the surveys.

We understand the need to elaborate on the overestimation of SWE in the second winter. We will provide meteorological data from a nearby site (<10 km away) which will help illustrate the mid-winter melt events. Unfortunately we did not observe the soil moisture conditions at this particular grassland site during the study period.

Detailed comments

L10-11 I suggest removing 'over shallow snowcovers' from the statement. Airborne applications using passive gamma-ray surveys have the capability to measure relatively moderate or deep snowpacks. The operational NOAA airborne gamma survey provides up to 1000 mm of SWE (https://www.nohrsc.noaa.gov/snowsurvey/historical.html; Mortimer et al., 2024).
Mortimer, C., Mudryk, L., Cho, E., Derksen, C., Brady, M., & Vuyvich, C. (2024). Use of multiple reference data sources to cross validate gridded snow water equivalent products over North America. EGUsphere, 2024, 1-31.

We will revise this statement to reflect the broader capabilities of airborne applications using passive gamma-ray surveys.

L81-82 A recent effort to address the issue of the antecedent soil moisture change for the airborne program using SMAP soil moisture was presented in Cho et al. (2020). It would be good to mention it here.
Cho, E., Jacobs, J. M., Schroeder, R., Tuttle, S. E., & Olheiser, C. (2020). Improvement of operational airborne gamma radiation snow water equivalent estimates using SMAP soil moisture. Remote Sensing of Environment, 240, 111668.

Thank you for pointing out the study by Cho et al. (2020). We will mention this work to provide context on addressing soil moisture changes.

Section 2.1 It would be much more helpful if general snow conditions are provided including annual SWE (maximum and range), snow covered duration, and onset/offset dates with some literatures if available.

We will include general snow conditions such as annual SWE, snow-covered duration, and onset/offset dates, as supported by literature.

L118 snow (water equivalent) → SWE

We will correct.

L141-142 For the stubble survey, how much did you expect that the larger GPS error ranges might impact the gamma SWE estimation? Please provide some justification regarding this.

We don't expect the larger GPS error for the stubble survey would have had a significant impact because this site was surveyed at a higher altitude (therefore larger footprint) – thus the GPS error would be partially compensated for by the coarser resolution. We will articulate this in the edited manuscript.

Figure 1. Have the authors considered providing some additional photos of both sites showing different surface characteristics along with the descriptions provided? I believe that would be informative for readers to better understand the sites.

We will consider adding additional photos for Figure 1 to provide this context.

L201 Should it be the equation "2"?

We will correct this.

L205 high resolution → high spatial resolution

We will correct this.

Figure 3 How were the mean biases calculated? What is the reference count rate to calculate mean bias at a certain integration time? Please describe it briefly. Also, why were the shapes of changes in mean biases with change in integration time different particularly between Fall Stubble and Spring Stubble? Were the changes negligible in terms of the amount of count rate?

We will provide a better explanation of the calculations used to create Figure 3. The mean bias for the static test is taken as the difference between the average count rate observed over the whole of the 75 second interval and the mean bias for the survey flights were taken as the difference from this reference and the average of the mean of the different integration times. There are some interesting contrasts in the shapes of the different mean biases shown, and upon reconsideration we feel that this approach does not communicate the signal stability/noise that we initially had in mind. In contrast, the CV of the integration time (right panel) clearly expresses the SNR to integration time relationship much more clearly and we will remove the mean bias (left panel).

Result 3.3 Please add the units of RMSE and mean bias (Figure 4) and the mean and uncertainty (Table 3). Also check the units throughout all figures and tables.

Units for RMSE, mean bias, and mean SWE values will be added and checked throughout all figures and tables.

L426 Please include the areal mean SWE values with the uncertainty for each season.
L426 2.5-hectare → 2.5 x 106 m2
L432 22.5 m spatial resolution
L432 Include the mean SWE value along with RMSE

L118, L201, L205, L426, L432: These specific line comments are noted and will be addressed accordingly.

We are committed to addressing each of your points thoroughly to ensure the manuscript meets the high standards of the journal and contributes significantly to the field of snow remote sensing. Once again, we appreciate your constructive feedback and look forward to improving our manuscript with your suggestions.

Sincerely, Phillip Harder, Warren Helgason and John Pomeroy