Review: Measuring prairie snow water equivalent with combined UAV-borne gamma spectrometry and lidar

The manuscript describes the demonstration of a new UAV-gamma spectrometer for measuring snow water equivalent over prairie snow in Canada. The results are assessed against SWE derived from UAV-lidar and manual snow density observations. Additionally, a fully contactless UAV-gamma+lidar fusion SWE product is demonstrated. To my knowledge this is the first demonstration of a UAV-gamma spectrometer applied over snow and provides the groundwork for future studies that may want to implement this new instrument at the UAV scale. The detailed considerations for flight planning and data acquisition that are presented will certainly be helpful for future studies using this instrument. The manuscript is generally well-written and organized and is suitable for publication in The Cryosphere. Below I have outlined the general comments that should be addressed prior to publication, followed by line-by-line comments. My comments are intended to be constructive and improve the overall manuscript.

General comments:

1. The main weakness of the study is the application of the manual density measurements in the reference dataset, the gamma and lidar fusion dataset, and in the defined uncertainty for the reference dataset. Figure 3 highlights large variation in density over the surveyed areas and simply taking the average density to represent the entire area introduces bias. Since this is the basis from which the SWE map is assessed, why were the locations of the density measurements considered? Were GPS points taken for each of the density measurements? I think a spatially interpolated density map would greatly improve the robustness of the analysis and the results for both the gamma SWE and gamma + lidar SWE. As for the uncertainty in the reference SWE, equation 4 describes the error in a single density measurement but does not represent the error propagation to SWE as a result of taking the average density over the survey area. The error in any given pixel should additionally contain the spread (e.g., 95% percentile) in density measurements over the survey area relative to the mean.

2. One of the main goals of the paper is to present a new instrument for measuring gamma rays, however the detailed description of the data collected by the instrument is not shown nor described in detail. Per the manufacturers website, the MS-1000 collects data for multiple radionuclides across spectral channels. Please include full details of the data collected and how the total counts C were calculated based on the collected data. An example of the collected data (potentially as a sub-figure in Figure 1) illustrating the collected data would be a nice addition that will help the reader understand the data collected with the instrument.

3. Units are missing in many locations throughout figures and tables, that I have noted below.

Line-by-Line Comments

Line 18: In the abstract the "reference dataset" is mentioned without context to what it is. I recommend briefly describing it here for clarity.

Line 22: I think this statement is somewhat misleading. The gamma+lidar fusion approach did not improve the results "substantially" and in fact the average site wide SWE measurement was slightly

worse compared to the gamma SWE measurement alone. What did improve substantially is the spatial resolution of the SWE distribution.

Line 25: Resolution is better described in terms of fine and coarse. I recommend that fine/coarse replace high/low when describing resolution.

Line 82: Missing the word "of"
 "Approaches to correct for overwinter changes require independent estimates of soil moisture change.."

Line 90: include the term "gamma" in UAV spectroscopy/spectrometry.

Line 95: The terms spectroscopy and spectrometry are used interchangeably in manuscript. I recommend choosing one of these terms and use it consistently, which should probably be spectrometry because that is the term used in the title.

Line 115: change was to were.

Line 116: "to" is not needed here.

Line 124: northwest and southeast are one word.

Line 128: snowpack should be singular in this context.

Line 152: Per major comment 1, please provide more information on how the spectral measurement was turned into count rates.

Equation 4: This equation describes the uncertainty for the density measurements, but it does not describe the uncertainty that is propagated to your spatial SWE reference dataset by using the average of the density measurements across the entire survey error. The uncertainty for any given pixel in the reference SWE map should be defined somehow based on the spread of the density measurements in Figure 2 if you decide to keep the analysis based on the average density.

Line 202-203: How was the lidar data interpolated? DIB or interpolation? Please add here.

Section 2.3.3: I don't understand why this analysis was not done spatially instead of using the average height and the average SWE from the two data products. This seems like a much more robust analysis and would make for a much stronger sensor fusion analysis.

Table 2: Add units to table. Also please add a statistic that describes the spread of the density measurements (i.e., 95 percentile, standard deviation, etc.)

Figure 2: Snow density needs units on the y-axis and in the caption, I am not familiar with any convention that uses (-) as a means to describe a density.

Line 229: Consider reminding the reader here what CV stands for. It is defined much earlier in text and I had to go back to remind myself.

Figure 3: What are the units of bias in this figure (y-axis). Could you provide some more context as to why some of these are positive and negative.

Figure 4: y-axis units missing on bias, RMSE, and n. Also is the red fall stubble line missing in the number of observations plot? If it is underlying one of the other lines please make visible by increasing the line width of the underneath line or using dashed line.

Line 256: Biases should be described as positive/negative.

263: "negative bias" used here, good!

Table 2: Table missing units.

Figure 7: Consider modifying the y-axis label so that it is clear that this doesn't refer to snow density. Also, would it make sense to add the gamma_lidar fusion distribution here?

Line 306: P should be rho.

Figure 8: Make clear which way the difference is done (ie., gam_lid – ref OR ref – gam_lid)

Line 344; ""…snowpack density changes…"'

Line 402: "be" not needed