Reply to Referee #1: Alain Royer

This paper completes the evaluation of the GNSS-derived approach for SWE monitoring using the retrieval algorithm already presented by Koch et al. (2019) and validated at the high-alpine site Weissfluhjoch (2540 m a.s.l), with data at 4 altitudes in the Alpes (820, 1185, 1510 and 2540 m a.s.l.). The performance of this approach is thus assessed for shallow to deep snowpack, with more frequent changes between dry- and wet-snow conditions at low altitude, potential differences in densification and a higher influence of rain events compared to the high-alpine site Weissfluhjoch (2540 m a.s.l).

This article first presents the uncertainty results for the Snow Water Equivalent (SWE), the Liquide Water Content (LWC) and the snow depth (HS) estimates derived from SWE and LWC retrieved data for each of the 4 study sites. The authors then analyzed the potential detection of snow variations over a short period of time (24 h and 72 h) by comparing these with reference precipitation data, and discussed the current limitations in retrieving new snow. Since the retrieval of HS estimates and LWC parameter are derived using a recursive process from previously retrieved data, the authors assess also the stability of GNSS-derived snow parameters regarding data gaps. Lastly, outlook on potential improvements are discussed (section 6).

General comments

The results part is well presented based on solid experiments (over 2 winters), with results that confirm the validity of the retrieval algorithm, showing a global relative uncertainty of about 11% compared to manual measurements and other sensors (Snow pillow and Snow scale). These results highlight the problem of certain assumptions used in the inversion (on density for example). Have you looked at the ice crust effect (melting/freezing, or after a rain-on-snow event) in the snow?

Manually observed snow profiles were performed weekly for the sites of Laret, Klosters and Küblis and bi-weekly at Weissfluhjoch. Although we observed some ice layers and occasionally in spring the formation of a thick melt-freeze crust, we could not attribute any particular effects on the derived SWE to these ice layers based on the limited data. We assume that the effects of individual ice lenses are marginal on the measured bulk SWE as the dielectric property of ice are much more similar to the one of snow compared to water in wet snow.
Regarding the rain-on-snow events, we occasionally had rain at the Küblis and Klosters sites. However, these rain-on-snow events were too rare and did not allow for a detailed analysis. Therefore, we cannot make any firm statements on their influence on the GNSS-derived SWE or HS as we showed in the graph in Appendix C. Still, we can exclude that the rain-on-snow events had any major effects on SWE and HS as those would be visible in the graphs in Appendix C. In this regard, more research on rain-on snow events may be needed – we will add a sentence on this limitation in the Discussion section 5.1.

It was foreseeable that the system would not be very efficient for monitoring precipitation events over a short period of time, given that the GNSS signal is integrated over 12 hours of measurements. This is a weak point of the system: 59% of events (Delta SWE>10 mm) was detected, see Table 3, but the exercise is interesting.

For the part of possible improvements of the system, it is clear that the current algorithm needs improvements, which are relatively little discussed in detail, but the authors argue that this was not the purpose of the article. OK

Regarding the improvement of snow height estimation, it is likely that adding GNSS signal analysis by reflectometry would improve the inversion process: but why was this not been done on the SnowSense? Are other specific antennas needed? More expensive? Longer processing time? Please specify.

This study was particularly designed and executed to check if the SWE algorithm already tested and validated at the high-alpine site Weissfluhjoch works as well at lower laying alpine sites using the same hardware and algorithm setup. In the past, reflectometry has been applied mainly with geodetic antennas. Only recently it has been shown that reflectometry works with low-cost sensors as well. However, implementing reflectometry within our current algorithm would require a considerable adaptation, proper testing, and validation, which was beyond the scope of this study. As mentioned in the paper, we plan for including reflectometry in upcoming studies. It would allow us to evaluate whether it is possible to use reflectometry-derived snow depth instead of the dry/wet snow density models we currently use.

I thus suggest “minor” correction with suggested clarifications.

Specific comments

- I suggest to use the term GNSS receiver (GNSSr) to name the snow measurement system based on GNSS signals.

To be in line with our previous study we would like to keep the term we used. The term receiver has already been used for the electronic component. In fact, the entire measurement system is more than the receiver as it includes also e.g. the antenna and the processing board.

- Introduction: I suggest to cite the recent review of SWE sensor (in review process, but probably published soon): Royer A., A. Roy, S. Jutras and A. Langlois (2021). Review article: Performance assessment of radiation-based field sensors for monitoring the water equivalent of snow cover (SWE). The Cryosphere Discuss. [preprint], https://doi.org/10.5194/tc-2021-163, in review, 2021.

Thanks for pointing out this new publication. We will certainly cite it in the Introduction section – and hope you will reference our article as well.

- In the whole article, it is rather an uncertainty that is evaluated than an accuracy, since manual or other references also have their own, sometimes significant, uncertainties.
For example, manual SWE measurement is subject to large variations and uncertainties, as studied in the revised version of Royer et al ‘s paper. Also, the Denoth system for measuring LWC can have large uncertainties (see the comparison paper: Mavrovic* A., J.-B. Madore*, A. Langlois, A. Royer and A. Roy (2020). Snow liquid water content measurement using an open-ended coaxial probe (OECP). Cold Regions Science and Technology. 171, 102958.)

We agree and accordingly will substitute accuracy with uncertainty throughout the manuscript where appropriate. We point out in both Results and Discussion sections that the reference data for LWC are subjected to a large uncertainty in both text and figure (see next answer). We will add the reference mentioned.

- What do the red vertical bars in Figure 6 correspond to, for the manual LWC measurements?

The vertical bars indicate the estimated error. We will specify this in the figure caption.

- L121: The given speed of signal propagation in dry snow depends upon the density!

That’s correct and we will point out in the revised manuscript that we used a mean value according to Schmid et al. (2014).

- L139 and 141: what would be the impact in the retrieval of the these assumed limits: (Ro_s,dry,max and Ro_s,0) ?

We do not think that discussing the impact of different model parameters is indicated at this point of the manuscript. These parameters were chosen to give best results for data at the location Weissfluhjoch (see Schmid et al., 2014). Changing these parameters will impact mainly the derived HS. As it was described in the Discussion (section 5.3) even a relatively large error in estimating HS has only a very small impact on the derivation of SWE.

- L200 Define the acronym LTE
We will refer to a mobile network data communication (LTE) module.

- Table 1 : precise the meaning of height of new snow (HN) and water equivalent of snowfall (HNW).

We will add in the figure caption that HN stands for height of new snow and HNW for water equivalent of snowfall.

- L401 The results of this paper for the retrieved wet-snow SWE appears significantly better than those previously presented by Koch et al. (2019) ?

The RMSE values of this study and Koch et al. (2019) cannot be compared directly. In this study, we compared the GNSS-derived SWE to manual SWE measurements. Whereas, as we explained in the following sentences (l. 401-404), Koch et al. 2019 compared the GNSS values with the automatic measurements from snow pillow and scale that exhibited significant errors at the beginning of the melt season. Therefore, the RMSE between the GNSS-derived SWE and the SWE measured by scale/pillow for wet-snow conditions is higher in Koch et al. (2019). We decided to base our comparison solely on the more trustful manual measurements because similar errors for snow pillow/scale were observed also in 2018-2019 and 2019-2020 (see Figure 3); moreover, for the sites Klosters and Küblis no scale or pillow measurements were available. We suppose that the accuracy was not lower in the former study – the difference is mainly related to the choice of reference data.

- Figure C1: Very interesting results! I might have put this figure in the results section! How did you differentiate between liquid and solid precipitations. The link between the amount of rain-on-snow and LWC would be original.

Indeed, it would be a very interesting link. However, at current stage, we think we have too few data to present significant results on this aspect. We hope to get more data including rain-on-snow events in the future to elaborate more on this. Regarding the discrimination between liquid and solid precipitation: as described in the figure caption, the precipitation was classified as snow below an air temperature threshold of T=1.1 °C and as rain above T=1.1 °C.