Reply to Referee #2: A.N. Arslan

General comments:

The tc-2021-235 manuscript, entitled," GNSS signal-based snow water equivalent determination for different snowpack conditions along a steep elevation gradient" presents the applicability of the GNSS-based SWE measurement at four different locations (820, 1185, 1510 and 2540 m a.s.l.) in the eastern Swiss Alps during two winter seasons (2018-2020). The aim of the study is to assess the performance of the GNSS algorithm which was described by Koch et al. (2019) and validated at the high-alpine site Weissfluhjoch (2540 m a.s.l) in the conditions of shallow snowpack, more frequent changes between dry- and wet-snow conditions.
As general comment, it is not evident that there are new conclusions on GNSS signal-based snow water equivalent determination rather than published ones as it is not clear whether different snow conditions studied newly; performance of the GNSS algorithm at 2540 m a.s.l. known and no much data at 820 m a.s.l. and not clear difference in snow condition at 1185 and 1510 m a.s.l. There was very good work done and analyses and conclusions were driven. Manuscript should be re-organized with a new title.

We regret that the novelty and differences to previous studies did not become clear. We will be happy to explain them once again.
Koch et al. 2019, tested the algorithm in detail at the high-alpine test site Weissfluhjoch, but it is still important to test and validate the method in lower laying regions with a shallower snowpack and more frequent changes from dry-snow to wet snow-conditions and vice versa as clearly mentioned in the manuscript. At the test site Weissfluhjoch, just one change from dry-snow to wet snow-conditions occurs in spring every year. The GNSS algorithm worked well with one seasonal change so far. However, at lower laying sites, the GNSS algorithm must change more frequently between different snow conditions. For example, by changing frequently between using the dry-snow density and the wet-snow density assumption.
Moreover, the snow conditions in Küblis, Klosters and Laret present some key differences: In Küblis, we only had a very shallow snowpack with predominantly wet-snow conditions including times with complete snow melt and small new snow events (season 2019-2020). Klosters, e.g., had more rain-on-snow events than the other stations. The total SWE varied also largely between the sites, e.g. for the season 2019-2020, the SWE in Laret was almost double the SWE in Klosters, but still approx. half of the SWE at the site Weissfluhjoch. In this context, it has to be mentioned that for a shallower snowpack, the portion of snow that is subject to daily melt-freeze cycles is larger and, therefore, the effect of the daily cycle is also larger.
We will add a sentence on this aspect in the Discussion section. In addition, we will explain the differences in snow conditions at the different elevations in more detail. We will also reformulate parts of the Introduction section and add a figure that illustrates the temperature evolution at the different sites and figures showing the rain on snow events for all sites.

Otherwise, we do not see any benefit in re-organizing the manuscript. We find the title and manuscript structure appropriate for the presented research question, results and conclusions.

Specific Comments:

Comment-1: It was said that the performance of the GNSS algorithm was validated at the high-alpine site high-alpine site Weissfluhjoch (2540 m a.s.l) (Koch et al., 2019). And this site was again listed as one of 4 sites to be assessed in this study. This makes a bit confusing. Were the same results used from Koch et., 2019 or new analysis were done and added to this study? This should be explained well, and necessary modifications should be done.

Actually, the time periods which were used in the current study and those used by Koch et al. (2019) are well defined in the papers. Koch et al. (2019) used data from the seasons 2015-2016, 2016-2017, and 2017-2018. The present study is based solely on data from the seasons 2018-2019 and 2019-2020.
In the present study, on one hand, we confirm the performance reported in Koch et al. (2019), on the other hand, more importantly, we compare the performance at the Weissfluhjoch site with the lower elevation sites; by doing so we can evaluate the performance for a much broader set of snow conditions.
We will emphasize more clearly that in the present study the data analyzed at the station Weissfluhjoch were solely from the seasons 2018-2019 and 2019-2020 .

Comment-2: In Line 205: It is said “We have chosen a 12-hour measurement period as it provides the best trade-off between accuracy and latency.” It would be good to explain this selection with a bit more justification if possible. As the GNSS algorithm was validated in higher -alpine site where less changes in snow conditions. Were there any data / graphs related frequent changes between dry- and wet snow conditions at four test sites selected? Linking to this, in figure 3, color bar given in time when dry-snow and wet-snow GNSS algorithm were used. How were these algorithms decided to use?

The current algorithm works sufficiently well, when the time window of satellite observation and data collection is more than approx. 6 hours as it is necessary to capture as many satellites as possible with both, ascending and decreasing tracks. One satellite pass is on average approx. 6 hours. We choose a larger 12-hour time window (whenever possible, e.g., season 2019-2020) to improve the accuracy with respect to a 6-hour period, but there is actually no difference in performance, if the time span would be increased to one sidereal day (which represents the entire coverage for the available GPS satellite before its repetition on the following sidereal day). We will add this information in Section 3.

The decision between dry- and wet snow-conditions is based on signal strength information as explained in Section 2 and Figure 2. We now included this information also in the caption of Figure 3. In addition, we also refer to Koch et al. (2019) for more detailed information on the algorithm itself and this particular decision step. We think this information should be sufficient to the reader. We also agree that changes between wet- and dry-snow conditions or vice versa can happen on a time scale shorter than 12 hours and will not be captured with the chosen data evaluation rate. Those rapid changes effect normally just the upper part of the snowpack and are relevant for the bulk properties only for a shallow snowpack. In general, the snow is classified as wet if a portion of the snowpack is wet for a short time span because the mean signal strength decreases sufficiently. In fact, we mentioned this issue in line 426 following: "The frequency of data sampling of 12 h used in this study did not allow to reveal the sub-daily wetting and refreezing cycle. However, LWC derivation at (half-)hourly frequency is possible and allows detecting sub-daily melt-freeze cycles as demonstrated by Koch et al. (2014) and Schmid et al. (2015)."

Comment-3: The aim of the study was said to assess the performance of the GNSS algorithm in the conditions of shallow snowpack, more frequent changes between dry- and wet-snow conditions. Looking at the figure 3, and again color bar where dry-snow and wet-snow GNSS algorithm used, it looks to me there were no frequent changes in snow conditions or? It would be necessary to give information on snow conditions at test locations.

Actually, there is a clear difference between the high-alpine site of Weissfluhjoch and the lower sites, which can also be seen in Figure 3, for example. At the high elevation site, the winter season is clearly divided in a dry accumulation and a melt season. For the lower sites it is different and melt (at least at the surface) occurs more frequently. The color bars in Figure 3 refer to the ''bulk'' state of the snowpack and do not reflect changes in only some parts of the snowpack. In fact, regarding daily melt-freeze cycles, for a shallower snowpack, the upper part has a large impact on the bulk value compared to a deeper snowpack where the effect is minor. We will add additional plots in the Appendices showing the frequency of rain-on-snow events and the temperature conditions for the four sites.

Comment-4: In Line 251: it is said that "For Küblis, only a qualitative evaluation was possible as there was hardly any snow during winter 2019-2020 and a long data gap in winter 2018-2019." Küblis 820 m a.s.l. (KUB) is important test location as lowest alpine-site where the conditions of shallow snowpack, more frequent changes between dry- and wet-snow conditions are higher probability as the purpose of the study. The Weissfluhjoch (2540 m a.s.l) site was already validated (Koch et al., 2019).

We agree that it would have been desirable to have more data for the Küblis site, but unfortunately due to pole tilting in 2018-2019 and almost no snowfall in 2019-2020, those are the only data we have. However, as shown in Figure 3 and Appendix C, also at the stations Klosters and Laret more frequent changes and rain-on-snow events were observed. We think it is important to compare the performance at the Weissfluhjoch site with the lower elevation sites and to have a broader set of snow conditions in our analysis. Even though, we have few data at the Küblis site, we reached our aim of evaluation the method at sites where frequent changes in snow conditions and rain-on-snow events occur.

Comment-5: In Line 589 in Conclusion: It is said that "Overall, our analysis confirmed that the GNSS system can reliably measure the seasonal evolution of SWE at different elevations where different snow conditions prevail. We conclude that the GNSS-based derivation of SWE is a valuable, affordable and reliable alternative to manual measurements or other automated SWE sensors; the method is in principle suited for operational SWE monitoring. Moreover, the GNSS method represents to the best of our knowledge the most appropriate and cost-effective approach for measuring SWE and LWC simultaneously, continuously and non-destructively."

In this conclusion, what is new? There was already published studies in high-alpine snow conditions and there were no good data in lowest al-pine, Küblis 820 m a.s.l. (KUB). Previous studies have also shown that the GNSS-based derivation of SWE is a valuable, affordable and reliable alternative to manual measurements or other automated SWE sensors; the method is in principle suited for operational SWE monitoring and etc.

As outlined above, the novelty is that we tested the method for low elevation stations where frequent changes in snow conditions and rain-on-snow events occur. We are pleased that the reviewer shares our conclusion that the method is suited. Only with extensive testing, however, it is feasible to operationally implement a new method, in particular in the context of high-quality, long-term data series that are of high climatological relevance.