Testing a novel sensor design to jointly measure cosmic-ray neutrons, muons and gamma rays for non-invasive soil moisture estimation by Gianessi et al. https://doi.org/10.5194/gi-2022-20

Author Response to Community Comment #1

CC: ***Community Comment,*** *AR: Author Response*

CC1: Dear authors,

I think that combining observations of neutrons for soil moisture estimation, gamma rays for distinguishing rainfall and irrigation as well as muons for correcting neutron observations as suggested by Stevanato et al. (2022) in a single sensor system is very interesting and would be a great advantage from a science and application perspective.

Cosmic-ray neutrons of different energies (e.g. Hubert et al. 2019) as well as muons (e.g. Braun et al. 2009) respond to solar events. As your observation period covers such an event, it poses an excellent opportunity to evaluate the muon data and their use for the correction of epithermal neutron observations. Thus, I suggest to add a time series plot covering the solar event (+/- a few weeks) showing the neutron monitor time series of the closest neutron monitors Jungfraujoch (JUNG) and Athens (ATHN) and the muon data of the four observation sites. A similar response to the solar event would underline the suitability of the sensor's muon product and the suggested correction approach.

Kind regards,

Daniel Rasche

AR: Dear Daniel Rasche, thank you for the comments and for the references. Based on your suggestions and from the comments of Reviewer #2, we have analyzed in more detail the dynamic recorded by neutron monitors (NMDBs) and the muons during our experiments. We present below a more comprehensive description of the results that we will integrate into the new version of the manuscript.

As shown in Figure 1 (top), the dynamics of incoming neutrons from NMDB (e.g., Jungfraujoch) and muons are generally well in agreement. We highlight however that some differences between the dynamic of NMDB and muons are identified (e.g., on 16th of July). These differences could be due to differences in local conditions, but this behavior is still under study. Noteworthy, the variability in incoming neutron and muon fluxes is in most of the period low and the differences between the two correction approaches do not significantly affect soil moisture dynamics computed therewith (e.g., Figure 1 bottom). For this reason, additional studies with longer time series and at different locations should be performed to test the use of muons for CRNS soil moisture corrections and to better understand these differences.

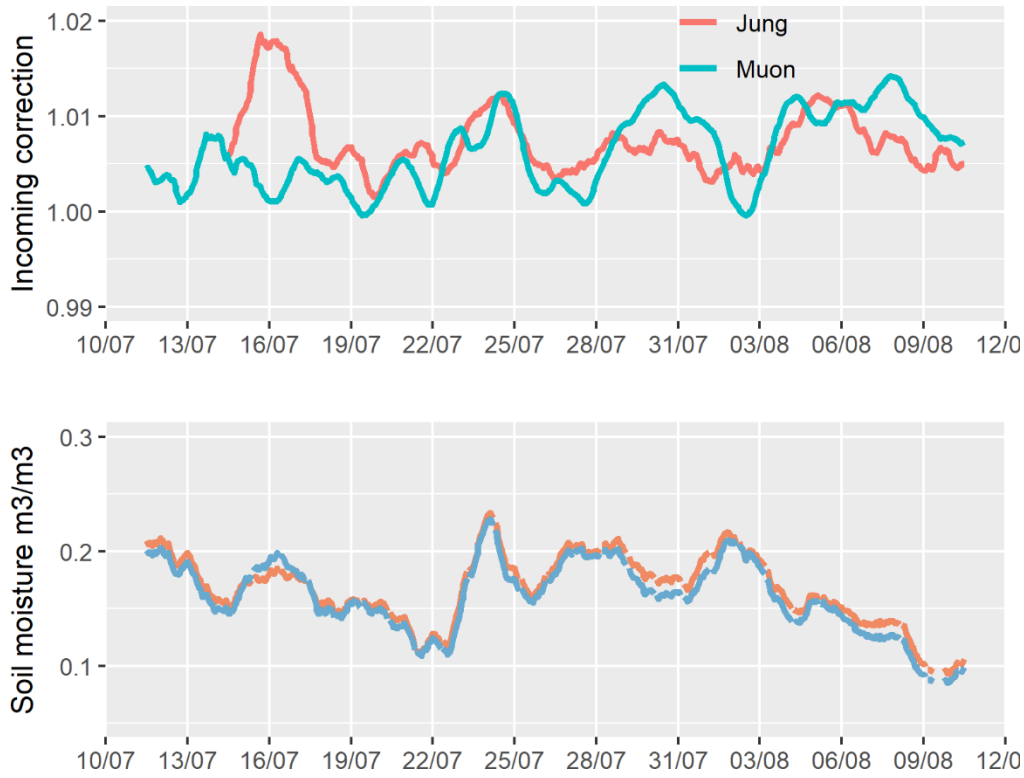

Figure 1. (top) Incoming correction factor based on neutron monitoring data base Jungfraujoch (Jung) and based on muon measured locally (Muon); (Bottom) effect of the different incoming corrections on estimated soil moisture at Ceregnano site.

The dynamics during the solar event on 4th of November is shown in more detail in Figure 2 below: from top, precipitation, muons and incoming neutron and muon fluxes, derived soil moisture at Ceregnano site, as example. As it is possible to see, in contrast to the general good agreement presented in Figure 1, the muon did not detect the strong and relatively fast drop in the incoming neutron fluxes measured by the NMDBs. At the current stage we cannot conclude about the reasons and we can only formulate some hypotheses.

On the one hand, we have to acknowledge that muon detector currently integrated in the Finapp3 sensor is not optimized for detecting fast changes: i.e., the detector is not directional (e.g., as a telescope looking upward) and instead it measures muon particles scattered from different directions, the counting rate is relatively low, and, also for this reason, the signal is processed smoothing the signal over days. The use of a bigger and directional detector for muon measurements to detect this relatively fast signal is, also for this reason, under investigation.

On the other hand, it is interesting to note the effect of the different corrections on the estimated soil moisture. As shown in the Figure 2 below, the solar event occurred during a precipitation event. As such, we should expect an increase in soil moisture. However, the soil moisture obtained using the incoming neutron fluxes for correction smoothed the signal. In contrast, the

soil moisture based on the muon shows a soil moisture increase. Also this hypothesis will be investigated in future studies with longer time series and possibly more solar events.

Overall, we want to underline also here that it was not the aim of the present study to conclude about the use of muons for CRNS soil moisture correction. In contrast, as discussed also in literature, this approach is at the early stage and only additional data will support this hypothesis and further developments. As also suggested by the Reviewer #2, sensors like the one presented in this study provides an excellent base to collect these new data. We will rephrase any statements that could be misleading, the figure and this discussion will be integrated into the new version of the manuscript.

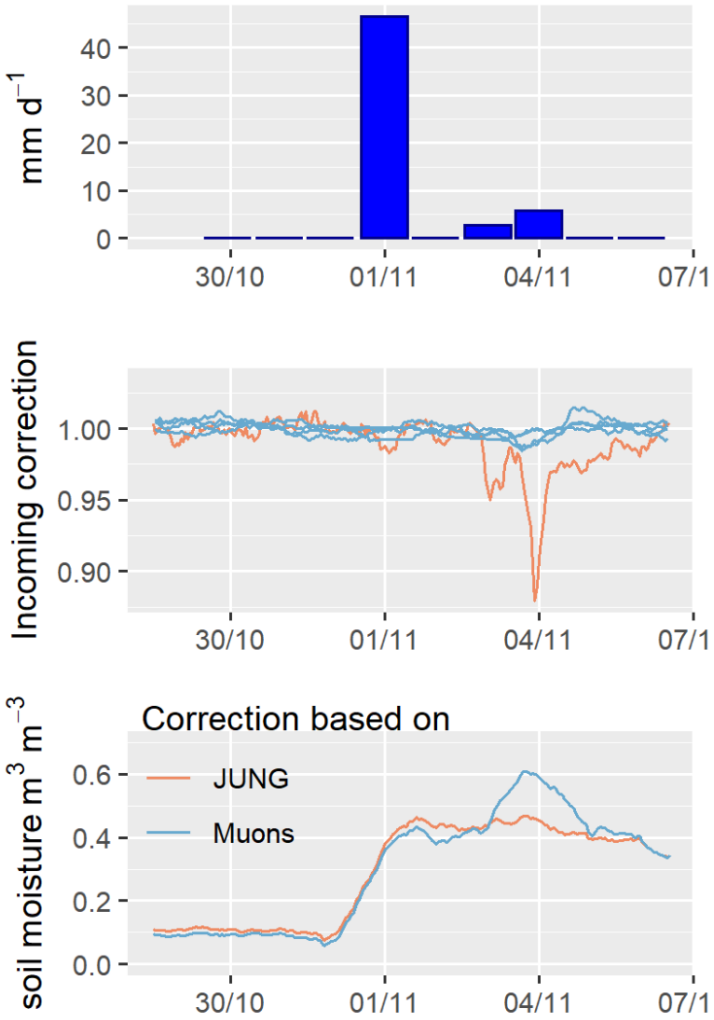

Figure 2: from top, precipitation, incoming correction, estimated soil moisture based on the different incoming correction at Ceregnano site, as example.