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 Editor

Comments from the Editor:

Dear Authors, Both reviewers have appreciated the revised version of your contribution to GI journal. Few suggestions are to be addressed. Best Regards, Jean Dumoulin

Dear Authors, Thank you for your revised version and the quality of the research work you made. I encourage you to take into consideration the last suggestions of reviewers in your final version. There are a few open issues, which, however, could be solved by simply fine-tuning the formulations in the text or some figures. I thank you in advance for this last effort. Best Regards, Jean Dumoulin

Dear Editor,

thank you for handling the manuscript and the overall evaluation. We are glad to know that you and both Reviewers appreciated our effort to improve the quality of the manuscript. We went through the new comments of the second Reviewer, and we agree that the new suggestions are also very valuable. Based on that, we provide a point-by-point response and a new version of the manuscript where we have rephrased some text and further improved some figures accordingly.

Please also note that the first Author Stefano Gianessi does not work anymore at the University of Bologna (Italy) but he is now an employee of FINAPP company. For this reason, we have made some changes in the affiliation to be consistent. Please check if it is in line with the requirements of the Journal.

On behalf of the Authors,

Gabriele Baroni

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Author Response to Reviewer #2

RC: ***Reviewer Comment,*** *AR: Author Response,* ☐ Manuscript text

RC: I appreciate the substantial changes to the manuscript based on the reviewer comments. There are a few remaining issues that I find not yet acceptable, but I see the paper on a good path to be published soon with minor revisions.

AR: Thank you for appreciating the scientific quality of the manuscript and for the additional suggestions to further improve the presentation quality. Point-by-point response to the comments is reported below. Based on that, we also provide a new version of the manuscript.

RC: Major

RC: - In general, I appreciate the conservative discussion of the results in the revised manuscript, but some formulations are still inadequate. The muon and gamma data do not show convincing agreement to scientifically expected results (low correlation to Medusa, no sign of FD events). At most, these results could be called "a first indication" that there is something behind it, but they need to be investigated in further studies (as was discussed, thank you). Still, I have to be strict here and point out some remaining inconsistencies that need to be reformulated to avoid misunderstanding and misinterpretation. Please see below.

AR: We put efforts to avoid misunderstanding and misinterpretation in the discussion of the results and we are glad of the acknowledgement of the Reviewer. These further suggestions are welcome and have been considered for further improvements.

RC: - Nov 2021 is a clear sign of a Forbush Decrease (FD). This effect has global influence on the neutron counts everywhere and should be corrected for all CRNS data. However, your Figure 8 indicates that the measured muons do not recognize the FD event, and are not very well in sync with the other features from JUNG, too. Hence, to me this is a clear indication that the measured muons are not suited for CRNS correction. You mentioned the reason that "FINAPP3 muon detector has been optimized to follow relative long-term variability (weeks to months)". How was this "optimization" done? Can't you show the original raw hourly muons flux? If the muon data is smoothed over many days, I won't consider it of any use for incoming neutron correction. In my view, this should be communicated as a major flaw of the method.

AR: We understand the concerns of the Reviewer, but we partially agreed with his/her opinion. On the one hand, these comments have been considered to better explain and discuss our results. Thus, some text in the manuscript has been modified accordingly as reported also below.

In the abstract, at L27 of the new version of the manuscript with track changes:

> The muons and the total gamma-rays simultaneously detected by the sensor show promising features ~~for a better correction of~~to account for the incoming variability and for discriminating irrigation and precipitation events, respectively.

At L364 of the new version of the manuscript with track changes:

> At the current stage, the reasons of these differences have been not identified but only some hypotheses are formulated. First, the FINAPP3 ~~muon detector has been optimized to follow relative long-term variability (weeks to months). The~~ muons count rate is relatively low and the recorded signal is smoothed over relative long-time period (days) to reduce the statistical errors. For this reason, short term dynamics cannot be captured. Second, the muon detector is also not directional (e.g., as a telescope looking upward) but it measures muon particles that are scattered in all the directions.

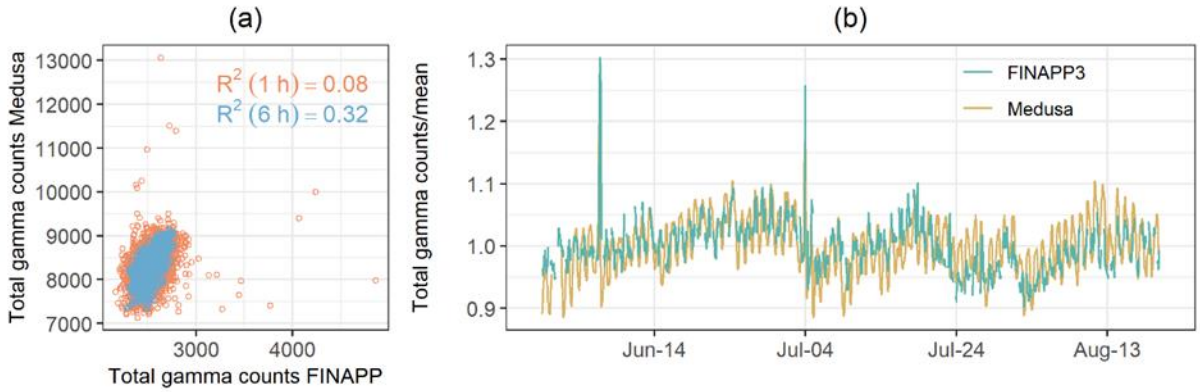
*On the other hand, we believe that we cannot conclude that our data show **"a clear indication that the measured muons are not suited for CRNS correction"**,* as suggested by the Reviewer and we disagree with his statement "***If the muon data is smoothed over many days, I won't consider it of any use for incoming neutron correction"***. It should be acknowledged in fact that incoming correction should not only compensate FD events or other fast temporal changes. In contrast, seasonal to yearly fluctuations of the incoming neutron fluxes due to, e.g., solar cycles, are also very predominant effects, especially for establishing long-term soil moisture monitoring. In addition, we agree that FD events have effects on neutron fluxes everywhere, but it should also be highlighted that the effects are of different degree depending on the locations. Noteworthy, a recent paper about incoming correction based on NMDB showed the use of a proportional factor to properly scale the signal measured at, e.g., Jung station, to locations with different characteristics (McJannet and Desilets, 2023). In the light also of this publication, it should be underlined that we should not blindly accept the fluctuation detected at, e.g., Jung station, as the correct one. Overall, we believe that the Reviewer is opening a very interesting discussion. We fully agreed on rephrasing some statements to avoid misunderstanding or any speculations, but we believe that further data and analyses are needed to have "clear indication" of the use of muons for incoming correction for both short and long term fluctuations. We believe that this has been fully acknowledged in several parts of the manuscript (see for instance in the abstract at L29) and for this reason no further comments have now been included.

RC - The authors have responded to the request for a comparison of the gamma sensor with a traditional gamma sensor by adding section 3.4. Here, the authors mentiond that the correlation is low (R^2=0.077) "mainly due to the presence of some outliers". This is not sound science. Please remove the outliers before publishing those results, or restrict the analysis to periods without precipitation. Otherwise readers cannot draw any conclusion from such a comparison.

AR: We believe that a comparison with raw data is still meaningful as it shows to the Readers an assessment if no post-processing is performed. For this reason, the plot and the discussion of the low correlation is not removed (R^2 value is only rounded to 0.08 to be consistent with the second reported value). But we agree and remove, however, these extreme values measured during precipitation events before smoothing the time series. The new correlation (R^2 = 0.32) is calculated now to this filtered and smoothed data. Figure and text have been changed as follows.

> The correlation between the two signals is low at 1 h time resolution (R^2 = 0.08~~77~~), mainly due to the presence of ~~some outliers~~extreme values observed during the precipitation events. The correlation increases (R^2 = 0.32) with a consistent detected dynamic (Figure 8b) when these

extreme values are removed, and the time series is smoothed over ~~at~~ a 6 h ~~resolution~~ time window~~(R^2 = 0. 29) and, at this time resolution, the dynamic is well captured (Figure 8b)~~.



RC- In the same section, the authors provide a 6h average of the data, present a correlation of R^2=0.29, and conclude "the dynamic is well captured". Again with a super-tiny plot with grey-in-greyish lines (Fig 9, right) and no-transparent super-thick point markers clumping above each other (left). It is impossible to visually identify any details, shifts, biases, lag times, etc. Please update your general presentation of the results (see cosmetics). Please also avoid calling these results "well capturing the dynamics". A rough tendency to follow the Medusa data is visible, but the low correlation and the significant deviations indicate that the data products represent different environmental effects and should be used with care. Please be more clear about this in the text.

AR: Thank you for the suggestion. We put some more effort for improving figure 9 and updated the general presentation of the results as suggested. See answer to the comment above.

RC - The authors now mention that "air temperature measured at 2 m hight provides a good approximation on the muon effect (de Mendonça et al., 2016)". From a quick browse of the cited study, I see strong complexity in this relationship, with seasonal temperatures in upper and lower athmospheric zones being completely out of phase in some regions of the Earth, while being similar in others. From this the authors should conclude that this is a serious issue that should be investigated in the future, instead of making the impression that taking near-ground temperature is a good and generally applicable approach.

AR: Our statement reported by the Reviewer seems misleading (to us as well) if extracted by the context. For this reason, we report below the whole text.

Noteworthy, the whole air temperature profile should be considered for the correction. This would better represent the atmospheric condition and it would better capture the effect on muons. Some studies, however, have shown how the use of air temperature measured at 2 m hight provides a good approximation on the muon effect (de Mendonça et al., 2016). This approach is used also in this study, but it should be further tested in future research.

It should be appreciated by the Reviewer by reading again the whole text, that we fully agree that the approach proposed by de Mendonça et al. is not taken for granted but should investigated in the future. In the discussion of the results this has also been highlighted. At L343 of the new version of the manuscript with track changes we state:

> However, the representativeness of air temperature measured at 2 m hight in comparison to the need of a whole air temperature profile is also questionable and it should be further investigated (de Mendonça et al., 2016).

Overall, we stated that the approach proposed by de Mendonça et al. is simple. But we did not conclude about the performance. We think that this is well conveyed in the manuscript, and, for this reason, no further changes have been made.

RC. Minor

RC. - Thanks for adding Fig. 7 to test the relationship of muons on athmosperic data. To me, the large spread in the correlation to air pressure is suspicious, maybe this indicates the influence of factors to the signal other than cosmogenic muons? It may be worth a note.

AR: Thank you. We have added the following statement to acknowledge the possible influence of other factors.

> The behaviour is attributed to the relative short time series and the small temperature range (±5°). However, the representativeness of air temperature measured at 2 m height in comparison to the need of a whole air temperature profile is also questionable and it should be further investigated (de Mendonça et al., 2016). The residual spread in the relationship suggests that the influence of factors to the signal other than cosmogenic muons cannot, however, be excluded and it should be considered in further studies.

RC- Eq 3: Do you mean 1+alpha instead of 1-alpha? Have you corrected for air humidity following Rosolem et al. 2013 properly?

AR: Thank you. The equation in the manuscript was wrong and we corrected it in the new version of the manuscript. We double checked the analysis and we confirm that was implemented properly.

RC: - It is not clear from the methods description nor Figure 3 where the Medusa system was located.

AR: Thank you. We added this information in the text and in the caption of Figure 3.

> For the assessment of the gamma signal measured by FINAPP3, a stationary CsI gamma-ray spectrometer (gSMS, Medusa Radiometrics, https://medusa-online.com/en/) has also been installed at Ceregnao site in 2021, few meters from the CRNS location.

> Figure 3. Experimental sites with FINAPP3 sensor (white points) and locations where gravimetric soil samples (red points) have been collected for comparison (pictures from Google Earth). At Ceregnano site, a gamma ray spectrometer was also installed few meters from the CRNS sensor.

RC: - It is not clear from the methods description in what year the measurements have been taken. The whole presentation appeared a bit complicated to me, as many different types of data have been recorded during many different periods, even at the same sites, but also among different sites. I'd appreciate an overview either in text, plot, or table, to better streamline the readers understanding.

AR: Thank you for the comment. All the measurements have been collected in 2021. We have added this information in the new version of the manuscript where appropriated and in the caption. We briefly report below where this information is indicated, and we believe now the Readers should not be confused.

In L165 of the new version of the manuscript with track changes:

> The recorded time series cover the period of seven months starting from May 2021 when, in both sites, a FINAPP3 detector was installed.

In L183 of the new version of the manuscript with track changes:

> A second assessment of the FINAPP3 sensor was carried out by a series of independent gravimetric soil sampling campaigns. The experiments were conducted in 2021 at four experimental sites located in the Po river plain, northern Italy (Figure 3).

In L255 of the new version of the manuscript with track changes:

> For the assessment of the gamma signal measured by FINAPP3, a stationary CsI gamma-ray spectrometer (gSMS, Medusa Radiometrics, https://medusa-online.com/en/) has also been installed at Ceregnao site in 2021, few meters from the CRNS location.

RC: - The authors added a zoom on on the neutron data comparison and I am ackowledging it. While the point cloud in the correlation plot is not insightful (better use smaller points of non-filled points or transparency), the dynamics of the neutron data looks convincing. However, the CRS2000 and Lab-C data seem to be more stable (right panels c and f). Is this due to the higher count rate, or could it be that Finapp sees other influencing factors, too? Maybe the uncertainty bands could be indicated or mentioned in the caption.

AR: Thank you for the suggestions. The correlation plot has been improved to better visualize the results. The uncertainty bounds would cover a bit the visualization of the lines. For this reason, we did not add uncertainty bands to better appreciate the (un)stability in the signal as detected by the Reviewer. We believe that this behavior is due to the lower counting rate. For this reason, we have stressed in the manuscript that more sensitive detectors should be foreseen when fast hydrological changes should be detected (see L270). No further changes have been made to the text.

RC: - For a more conserverative formulation, I'd suggest to change in the conclusions "Muons were found to be a possible alternative for incoming correction for CRNS application" to "Muons were found to be a potential candidate to support the correction for incoming cosmic rays."

AR: Thank you. The text has been changed as suggested.

Muons were found to be a potential candidate to support the correction ~~a possible alternative~~ for incoming ~~correction for CRNS application~~cosmic rays

RC: - The sentence in the conclusion is misleading: "On the other hand, the use of gamma-ray spectrometry was identified as an alternative method for non-invasive soil moisture estimation.". I'd assume that you are referring to the cited paper who found this. But it was not found in your study as no spectrometer was used. Make more clear that this has been found by authors which is what motivated you to test a total gamma counter (which led to different findings).

AR: Yes, the Reviewer is right. The statement refers to previous studies where gamma ray spectrometers have been used. The text has been changed and the citations better placed to avoid misunderstanding as follows.

In previous studies, ~~M~~muons ~~-~~muons were found to be a potential candidate to support the correction ~~a possible alternative~~ for incoming ~~correction for CRNS application~~cosmic rays (Stevanato et al., 2022). On the other hand, the use of gamma-ray spectrometry was identified as an alternative method for non-invasive soil moisture estimation (Baldoncini et al., 2018) and irrigation discrimination (Serafini et al., 2021).

RC: ## Cosmetics

RC: - It is very hard to identify dates within the plates for international readers. X tick marks like "03/07" are not very helpful and very confusing. Please use informative tick marks like "Jul 03". Also, most plots do not show a year, not even in the caption. It could be added to the first tick mark or to the caption.

AR: Thank you for the suggestion. We changed the X tick. Since all the data have been collected during the year 2021, we added this information to the caption. See the new version of the manuscript.

RC: - Most plots are very hard to read due to small panel size and greyish look. Avoid grey background, use clean, thin, black-and-white axis objects to increase the contrast, avoid colors whenever possible, choose meaningful axis ticks (see above), use column headings to highlight which panels correspond to which sites (e.g., Fig 8). Generally, consider using full-width plots for time series data instead of narrow panels that barely span 20% of the page width.

AR: We put some additional efforts to improve the quality of the plots and we hope now they have reached the right quality for publication.

References

McJannet, D.L., Desilets, D., 2023. Incoming Neutron Flux Corrections for Cosmic-ray Soil and Snow Sensors Using the Global Neutron Monitor Network. Water Resources Research n/a, e2022WR033889. https://doi.org/10.1029/2022WR033889