Interactive Discussion: Author Response to Referee #1

Assessing the feasibility of a directional CRNS-sensor for estimating soil moisture

Till Francke et al.
Geoscientific Instrumentation Methods and Data Systems, Discuss., doi:10.5194/gi-2021-18

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

Dear Referee,

thank you very much for your positive comments and constructive suggestions to our manuscript. We very much appreciate the time and effort that you have invested in your report.

Based on your report, we have already started to revise our manuscript. Please find below our detailed responses to all the points you have raised in your report. We will continue to address these points, and are confident that the manuscript will substantially improve as a consequence. Yet, the final implementation of changes will also depend on another referee report that is still to be submitted in the interactive discussion.

Kind regards,
Till Francke
(on behalf of the author team)

1.1. General comments

RC: ***Review of manuscript titled "Assessing the feasibility of a directional CRNS-sensor for estimating soil moisture". The idea is fantastic and very much needed. I think this is study that will gain the interest of the research community. The main limitations of the manuscript are:***

- the assumption that readers are familiar with the cosmic-ray neutron sensing technology for measurement of soil moisture.

AR: We indeed consider our manuscript to address readers familiar with the basic concept of CRNS. However, we will add some introductory information in this regard to section 1.1.

RC: ***- The manuscript is dense and the logical arrangement of ideas together with some limitations in the English language makes this paper difficult to read. It starts by describing a previous directional sensor, but then it shifts the attention to simulation work, without interconnecting both. It seems to me that the manuscript could be much shorter and more straight to the point***

AR: We are confident that the reviewers' suggestions (below) will help to improve the legibility of the manuscript.

The description of the existing directional sensor is meant as a justification why we chose to simulate this very realization of a shielded instrument as an example case, as other designs are likely imaginable. We will strengthen this reasoning and interconnecting both parts.

RC: ***At time it seems that this manuscript could have been partitioned in two different manuscripts parts: a more theoretical description of the error sources, propagation, and computation of directional neutron counts, and a second part about testing the quantitative reasoning with a modeling effort.***

AR: These two parts are actually already distinguished in the "Method" subsection (2.1 and 2.2.) and the corresponding "Results and Discussion" subsections (3.1. and 3.2): *.1 deals with the numerical modelling, necessary to understand the relevant effects and determine actual parameter values for describing them (e.g. β), while *.2 generalizes these findings to a broader range of settings in terms of count rates, signal contrast and aggregation times. We will improve the description of these two pillars in the introductory sentences of the "Methods" section, and try to clarify the fundamental link between the two.

RC: ***The "Limitations and Outlook" section contains valuable information for the research community. I suggest condensing this section into a fewer, but still relevant, number of points, or merging the points into a narrative. With so many bullet points I question the usefulness of the current layout. Even this section could be interpreted as a potential technical note or manuscript presenting and discussing limitations and opportunities of directional detectors.***

AR: We agree that the current layout is unfortunate. We will restructure the section by grouping specific items in meaningful sub-topics, e.g. "Simplifications", "Parameters used in the study" and "Potential for further instrumental improvements".

1.2. Specific comments, details

RC: ***Line 14. Define again the abbreviation for Cosmic Ray Neutron Sensing (CRNS) in the manuscript narrative.***

RC: ***Line 14-15: The first two sentences can probably be merged into one. Consider the following alternative: "Cosmic Ray Neutron Sensing (CRNS) has been widely adopted in the past decade to measure soil water content in environmental sciences" or this one "In the past decade, the adoption of Cosmic Ray Neutron Sensing (CRNS) has increased considerably to measure soil water content in hydrological, agricultural, and environmental research applications (Zreda et al., 2008)"***

RC: ***Line 15. Unclear statement "in both research and application". Research could be basic or applied, so its unclear whether the authors refer to applied research or applications beyond research (end user or consumer applications). Please clarify.***

RC: ***Line 17. Remove the first "or" so that ". . . , to support irrigation management. . . "***

RC: ***Line 22: Re-word to "a depth of a few decimeters" It may be good to provide a quantitative range. It seems that the typical sensing depth oscillates between 10 and 40 cm depending on the soil moisture conditions.***

AR: –> All suggestions above have been / will be implemented.

RC: ***Line 25. This paragraph probably needs more context and depth. At this point it's not obvious that the CRNS is omnidirectional, so it may be good to state that this is the nature of current measurements and available instruments. I suggest briefly expanding more on the issue of instrument omnidirectionality (why is it this way?) and other factors such as soil spatial heterogeneity that can create soil moisture spatial patterns. I think this paragraph would be essential to understand the motivation of the study.***

AR: We will extend the paragraph with these suggestions.

RC: ***The "larger spatial support" compared to what measurement? point-level?***

AR: The comparison refers to classic point scale measurements. The sentence will be modified accordingly.

RC: ***Line 30. Specify that the "energy level separation" is for the spectrum of cosmic-ray neutrons.***

RC: ***Line 33. Consider a better transition here. For instance: "An approach to reconstruct sub-footprint patterns in soil moisture consists of using a dense.... (Heistermann et al., 2021). Although..."***

RC: ***Line 39. Consider merging this paragraph with the previous since it's a continuation of the same argument.***

RC: ***Line 44. I would like to suggest the use of the following terms: "Directional neutron sensing" or "Cosmic-ray Directional Neutron Sensing"***

RC: ***Line 48. There seems to be a typo here: "and/and"***

RC: ***Line 50. Consider replacing "defense" with military applications***

RC: ***Line 51. There is an extra ")"***

AR: –> All suggestions above have been / will be implemented.

RC: ***Line 55. This paragraph seems too short at only two sentences long. I suggest detailing the type or energy level of the incoming neutrons. It's unclear from the text whether the authors are referring to thermalized or epithermal neutrons. It will also be important to highlight that the term "directional" in the context of this paper mostly applies to the horizontal plane.***

AR: The paragraph has been merged with its precursor. However, we do not think that in this context the energy level of the neutrons is of relevance and prefer to keep the message of the paragraph simple. A note on focusing on the *horizontal* aspect has been added to the end of section 1.2.

RC: ***Line 59. Spell out "PE" (polyethylene?). Was this a high-density PE?***

AR: PE spelled out. Mitrofanov et al. just report about the use of "polyethylene", leaving it open whether it was HDPE or not.

RC: ***Line 61. How is Ntotal observed or computed? Is this the total considering the shielding or the total without it? I assume that for simultaneous collimation efficiency you need two devices or alternatively the same device with and without the shielding over short periods of time.***

AR: The description was ambiguous and modified to

> [η] being the ratio between counts from the targeted FOV N_{FOV} and the total counts N_{total} registered by the detector, i.e. counts from any direction.

Thus, N_{total} is the observable variable, which can directly be measured by the directional detector. No concomitant operation of an unshielded detector is required.

RC: ***Line 70. Please, clarify whether the unshielded side means less shielding to avoid confusion with a bare detector. For instance, the CRS 2000B already includes some shielding to attenuate neutrons. This means that the authors added an extra layer of shielding.***

AR: We added the sentence

This shielding is independent of the moderator already in place used to thermalize the neutrons.

RC: ***Line 73. Replace 2Pi by 360 degress. What do the authors mean with "flexible"? What is the integration time at each angle? or is it a continuous scanning? I think that a few more details will allow readers to reconstruct the idea and reproduce the study.***

AR: Changes made and requested information added:

This could be operated to cover the full 360° periphery (2π) in flexible angular sections with configurable integration times at selected positions, and thus allow for measurements with variable directions producing time-series of count rates for different FOV in the footprint.

RC: ***Line 99. Would this bycatch flux be similar regardless of the gas used in the detector (^{3}He vs ^{10}BF3)?***

AR: The mentioned 'bycatch' depends to a minor extent on the gas type, gas pressure and moderator configuration. The deviations are insignificant for the purpose of the discussion.

RC: ***Line 109. Emphasize that these settings are in the detector electronics. Can you add the model of the neutron pulse analyzer from Quaesta?***

AR: We changed the wording to "... threshold settings in the electronics " to underline the fact. There are various forms of non-neutron signals. Some of them can be cut by setting lower and upper thresholds on the detected pulse energy. In the case of radioimpurities their signatures are often indistinguishable from neutrons in case their energy lies in the range of those of neutron conversion products. With usual electronics, independent of the manufacturer, such cannot be discriminated against. They form a plateau 'under' the neutron events.

RC: ***Lines 126. The wording in this sentence implies that there is an "unshielded side", which most people will take as a bare detector, which I suspect is not the case here.***

AR: To avoid this potential confusion we have added the following sentence to the end of section 1.1.:

The term "shielding" is often used to denote parts around the detector to moderate ("thermalize") high energy neutrons to be detectable. Here, we will use the term "moderator" for this component, while components aiming to achieve directionality are referred to as "shielding".

RC: ***Figure 2. I like this figure. To make it a bit more explicit it will be good to add in the description the meaning of the shaded area. Are the arrows pointing in the "increasing" direction? Perhaps adding a "+" and "-" symbols could help the reader. Will it be possible to add magnitudes to the axes and denote with a point the selected combination for this study?***

AR: The shaded areas have no actual meaning apart from being not part of the inner triangle. To avoid this confusion, we have modified the figure, its caption and added "+" and "-".

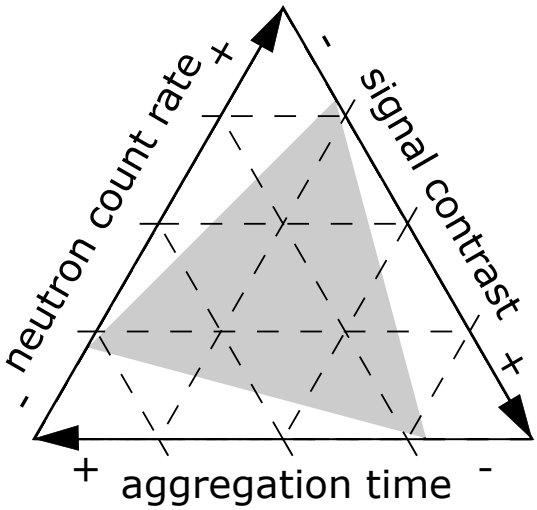

Figure 1: "Tradeoff-triangle" in directional CRNS-measurements as ternary plot: for a given combination of two of these parameters, the third parameter must be adjusted accordingly to obtain the requested accuracy. The inner triangle (grey) illustrates the parameter space for an increase in required accuracy. The straight outline here is only chosen for the sake of simplicity and could be curved instead.

We intend this figure merely as a conceptual illustration of the trade-off problem. Thus, we'd rather refrain from adding actual numbers. Moreover, the performed multi-dimensional analysis of each of the three factors would result in multiple inner triangles, which would unnecessarily complicate the figure.

RC: ***Line 129. Unclear whether the authors are referring to the area in the FOV (i.e. area of the open side of the instrument) or the horizontal area part of the sensing footprint.***

AR: We have added a reference to Figure 3 to make clear that area refers to the part of the footprint.

RC: ***Line 141. While in situ experiments controlling the neutron flux are impractical, in situ validation of the approach is not. For instance, a field validation could be done by intensively measuring soil moisture. For this to work a field with a known directional variability may need to be selected. I just wanted to emphasize that in situ validation may not impractical (in terms of measuring soil moisture).***

AR: We agree that controlling the flux rates in two half-spaces via adjusting the soil moisture is, in theory, conceivable. However, judging from our experience with much simpler efforts to reliably ensure (let alone adjust and hold) the soil moisture to desired values in test sites of adequate size, we replaced the term "impracticable" with "difficult to implement".

RC: ***Line 149. I like the first question, but it may need to be formulated differently. As it stands now it will be more relative to the ability to regulate the rotary mechanism than the detector itself.***

AR: We posed the question in the most general way. As the results later will show, the required aggregation times

are in the range of hours, so the velocity of the rotary mechanism is by no means a limitation. However, to avoid the confusion, we have replaced the term "scanning" (implying continuous rotation) by "directional measurement" (measurement with variable, but temporally constant orientation) throughout the manuscript.

RC: ***Line 150. The authors vaguely described what is meant with "contrast". Perhaps a bit more background on this metric would be helpful. Most people are familiar with count rates and integration time, perhaps less familiar with signal contrast (unless the authors are referring to signal-to-noise ratio)***

AR: The description of "contrast" three paragraphs above has been extended.

RC: ***Line 151. What is a robust estimate? It would be nice to provide a more objective metric, perhaps in terms of error in volumetric water content (or the equivalent neutron count).***

AR: We deliberately used the general expression "robust metric" here, as robustness can be related either to *distinguish* or to *determine* rates, as explained in the sentence following question C.

We also strictly limit the analysis to the count rates, not soil moisture, for the reasons stated in the "Limitations" section:

> This study exclusively considered count rates as the target observation variable. However, for application, count rates are merely a proxy which need to be converted to the actual quantity of interest, namely soil moisture, snow or biomass. The relationships used in such conversion (e.g. [**?**]) are not linear; instead, they saturate with increasing hydrogen pools and low count rates. [...] Combining the presented approach with the one of [**?**] would allow the direct quantification of uncertainty for the target variable.

RC: ***Line 165. Is the stretch of 600 m in all directions? or just in the horizontal direction?***

AR: 600 m is meant as the minimum horizontal extension for the application of URANOS (see RC Line 181). The air buffer layer is, as stated later, recommended to be constructed as a 1000 m thick column.

RC: ***Line 169. Please, adopt the term particle density which is more commonly used in the soil science literature over "compound density".***

AR: Change made.

RC: ***Line 172. This is what I meant earlier about "further" moderating the detector.***

AR: The sentence has been rephrased to

> In order to assess the effect the additional moderating effect of the directional shielding on the measured intensity...

RC: ***Line 181. The virtual detector is within a domain of 800 x 800 m, but the authors defined earlier that the domain was only 600 m. Please clarify.***

AR: The paragraph "Neutron simulation model URANOS" is a general introduction to the URANOS Monte Carlo model. We have rephrased the sentence of concerning 'at least 600 m' there. The following paragraph "Scenarios simulated with URANOS" containing the specific number 800 m refers to the setting used in this study.

RC: ***Line 194. Is this FOV of 180 degrees something that would be possible with an actual instrument? From figure 1 it seems more like 90 degrees.***

AR: For clarification, we have added the sentence

> This value [of the FOV] has no direct relation to the geometry of the opening face of the shielding. Instead, it is an arbitrary decision to target the area within the FOV with the measurement.

RC: ***Line 195. In this section, are the authors referring to count rate based on raw neutron counts or on corrected counts by atmospheric conditions and incoming neutron flux?***

AR: Any correction (incoming, barometric, water vapour) would linearly affect all mentioned rates the same way, so the given equations hold for either.

RC: ***Line 201. Remove word "Please".***

AR: Done.

RC: ***Line 202. Why not abbreviating gamma as "D" (directional) and "OD" (omnidirectional) or "uni" and "omni" for better readability across the manuscript.***

AR: We changed the notation to γ_{D} and $\gamma_{!\mathrm{D}}$ for consistency with our notation. This also affected R_{s} being changed to R_{D}.

RC: ***Figure 4. Please indicate in the caption the assumption that R1total < R2total (I assume this since the bars for total counts are different for R1 and R2). Although I'm confused since in Line 215 it says that there is no fundamental different between A1 and A2.***

AR: Line 215 was ambiguous, we rephrased to

> The directional detector may be oriented towards the left half plane A_1 or the right half plane A_2. Formally, there is no fundamental difference in the equations for each and we exemplify the next step with the one oriented towards A_1 and its count rate $R_{\mathrm{f1,alb}}$.

RC: ***Lines 290-300. These sections probably need to be merged into a single section and presented as separate paragraphs. The "Count rate" section is only one sentence long.***

AR: We changed all subsection headings to simple bold face font like this:

> **Fraction of non-epithermal counts** (ϵ): In the examples, we illustrate ...

RC: ***Line 319. How much higher is the reduction in count rate by adding the shield beta in wet conditions? Even a speculation would be fine here. Perhaps the authors can use soil saturated conditions as a reference. Do you need to add a reference to Table 3 in this statement?***

AR: Actual values for β can be abstracted from the table. We clarified this by modifying the sentence to:

> Secondly, the total count rate reduction by adding the shield, β, is at least 30 %. For the wetter conditions, it is even higher, reaching β=40 % for θ=50 % (see **??**).

RC: ***Table 3. What is the integration time of these neutron counts? Are they corrected for atmospheric conditions? Is the "no shield" term referring to a bare detector or to the portion of the directional detector with "less" shielding? Please clarify.***

AR: All details given in section 3.1 result from the neutron simulation, with its details given in section 2.1. The integration times (i.e. total counts simulated) have been chosen to yield sufficiently robust statistics. Corrections would have no affect on the ratios reported here (see reply to RC Line 195). "No shield" refers to the omnidirectional detector, as now clarified in the text (see reply to RC Lines 126).

RC: ***Line 354. I'm starting to think that it is hard to remember what "worstcase" scenario means at this point. The definition of this term occurred several sections above and the name does not seem intuitive. I wonder if there is a better way of naming.***

AR: We had used the terms "pessimistic" before, but found this to sound too subjective. "favourable" and "unfavourable" could be an option, which we would implement.

RC: ***Figure 9. Please specify for which sensor form factor this figure applies. Does this figure translate to other detector configurations?***

AR: All computations refer to the sensor geometry described in Fig.1. This point is also addressed in the Discussion, but will be more prominent after the restructuring of this section (see RC "Limitations and Outlook")

RC: ***Line 410. Larger planar shielding in what direction of the instrument. It will be good to provide a more explicit comment for other researchers that want to replicate or design their own directional detectors.***

AR: The respective sentence was modified to

> Other designs (e.g. larger vertical planar shieldings blocking off one half space) may provide superior characteristics, namely η, which could be assessed by further neutron simulations.

RC: ***Line 396. How does this integration time relate to typical applications for soil moisture sensing in agricultural and hydrological scenarios? It will be good for the authors to expand on the practical applications/obstacles of the required time integrations and counts required to achieve a certain precision.***

AR: We are somewhat hesitant to claim general figures on what aggregation times are required, as they may be highly application-specific. However, we now refer to the respective explanations given before and modified the sentence to

> 1, 6, 12 and 24 h. Longer aggregation times are not recommended from a hydrological perspective, since they would commonly imply too high a change of the observed variable during that interval (e.g. due to rainfall or drying and respective change in R.