Interactive comment on "COSMOS: The COsmic-ray Soil Moisture Observing System" by M. Zreda et al.

H. Bogena (Referee)

Reviewers's comments are in black.
Responses by Zreda et al. are in blue.

General comments:

1. The monitoring of cosmic-ray neutrons is a promising way to close the gap between point measurements and remote sensing. This paper describes the cosmic-ray soil moisture measurement method, the instrument and its calibration, the design, data processing and dissemination used in COSMOS, and give example time series of soil moisture obtained from COSMOS probes.

Response: None necessary.

2. Although some general papers on the methodology of the cosmic-ray soil moisture measurement technique already exists, the paper gives some valuable further information on the processes leading to the neutron generation due to cosmic radiation which helps to better understand the technique and to interpret the neutron count data.

Response: None necessary.

3. However, the paper is at times written like an advertising text, like for example the first sentence "Area-average soil moisture at the sub-kilometer scale is needed but until the advent of the cosmic-ray method it was difficult to measure". As being a user of such an instrument I have experience with the interpretation of the CRP data which is not easy in certain environments (especially humid climates) because the sensitivity of the cosmic ray sensor decreases with increasing soil moisture content.

Response: The language has been changed to be less like advertising; specifically, the sentence mentioned by the reviewer has been removed. Also, we indicated that there are other methods (i.e., distributed sensors networks, with reference to Bogena et al., 2010) for obtaining area-average soil moisture. We agree with the comment on sensitivity, and we point out here that the decreased sensitivity with increasing moisture level is clearly visible in the calibration function (original Fig. 7, new Fig. 6). This is an inherent limiting factor of this method, not unlike many other methods that also have non-linear response functions.

4. The authors introduce the new name "neutronavka" for the sensor. Since the name "cosmic ray probe" or short CRP is already well established I would suggest to keep this name in order to avoid misunderstandings. Also other names like, e.g. COSMOS probe, should be changed in to "cosmic ray probe" or short CRP.

Response: We agree. The term "neutronavka" has been replaced by the term "cosmic-ray probe" throughout the paper. However, we prefer to keep the term "COSMOS probe" to mean a cosmic-ray probe used in the COSMOS.

5. I have observed several redundancies due to the structure of the manuscript (see specific comments).

Response: We knew that there were redundancies, but in order to make the text complete it is difficult to remove all of them. However, we did minimize them: for example, we combined setions on production of cosmic ray neutrons into one (section 2.1), and that section is now separated from section on moderation (2.2).

A more detailed analysis of more than two sites of the COSMOS network should be included to better confirm the statements made in the manuscript.

Response: We have not conducted detailed analyses of other COSMOS data, but we show two example data sets that tell interesting stories. One is from Colorado and comprises data from two probes at a single location but at different heights above land surface (1 m and 20 m). The second data set is from the Island of Hawaii and comprises data from two probes at two different altitudes. These data are preliminary: they have not been analyzed and interpreted as well as those from the Santa Rita and San Pedro sites. [Sections 3.4.2 and 3.4.3 of manuscript.]

Specific comments:

P2 L29 Recently wireless sensor networks have been developed that allow for real-time measurement of soil moisture pattern dynamics from the field to the catchment scale

Response: Added a reference [p. 2, l. 27 of new manuscript] and a sentence about distributed sensors network and cited the paper by Bogena et al., 2010. [p. 3, l. 8]

P3 L4-7 Intermediate scale soil moisture can also be measured using wireless sensor networks (e.g. Vereecken et al., 2009, Bogena et al., 2010).

Response: Added a sentence about distributed sensors network and cited the paper by Bogena et al., 2010. [p. 3, l. 8]

P3 L23-32 This section is very general and should be shortened.

Response: Agreed. This section has been shortened by approximately one-third of the original. [p. 3, l. 24-32 and p. 4, l. 1-6]

P5 L13 Fast neutrons are only produced via the evaporation process?

Response: It is not the only process. Radioactive decay also produce fast neutrons (for example, a radioactive source of fast neutrons is used in the conventional neutron probe). But this production mechanism is of secondary importance here and any radiogenic fast neutron background will be constant at any one site, so there is no need to go into non-cosmogenic production of fast neutrons.

P6 L12 The production of neutron has already been described in the previous chapter. This chapter should exclusively deal with the moderation of fast neutrons.

Response: Agreed. The text dealing with production is removed from this section (it has been placed in the previous section, 2.1, to make it more complete).

P6 L13 Neutrons can also be produced by other compartments like e.g. biomass, surface water.

Response: Yes, they are produced in all earth's materials. The relevant sentences have been modified to indicate this. [p. 5, l. 14, p. 6, l. 4, p. 9, l. 13-15]

P6 L14-15 It should be noted that the moderation of fast neutrons is caused by elastic nuclear collision.

Response: Yes, it is mostly elastic collisions that moderate fast neutrons. The relevant sentence has been modified to indicate this. [p. 7, l. 4]

P7 L7 Manganese is not included in table 1.

Response: Our mistake. Manganese was changed to iron in text (iron is in Table 1), and the number of collisions was changed to 505 (consistent with the value given in Table 1). [p. 7, l. 27-29]

P7 L22 Fig. 6 should be reduced to 3 cases since 0 kg/kg water content is not possible due to the presence of lattice water.

Response: It is true that most rocks/soils contain lattice water and therefore the top panel in Figure 6 is unrealistic. But we wanted to illustrate, on hypothetical chemistry, how the small amounts of water shift the moderating power from mostly oxygen (60%-80% for zero water content, top panel) to mostly hydrogen (>50%) at water contents as low as 1 kg kg-1, regardless of the chemical composition of the rock/soil. Omitting the zero water content panel would omit that important point. We felt compelled to keep the figure unchanged.

P8 L1 There is a large overlap of this chapter with the two previous chapters leading to redundancy. Therefore this chapter should concentrate on the measurement aspects, which are described in sections 2.4 and 2.5.

Response: Agreed. These parts in question were moved to previous sections (2.1 and 2.2), and sections 2.3, 2.4 and 2.5 focus only on measurement aspects.

P8 L11 In reality the production rate for a specific site is not known since there are several unknown influencing factors.

Response: Correct – its is not known explicitly, but it is known implicitly once the probe is calibrated on independently measured soil moisture (via calibration parameter N0). New text has been added to indicate this. [p. 8, l. 7]

P8 L25-26 How much is the production rate influenced by the soil water content?

Response: My guess is that it varies by a few percent. But it is difficult to ascertain because in MCNPX it is difficult to isolate and tally fast neutrons as they immediately undergo moderation. In the neutron transport model MCNPX the production rate is automatically updated when water content changes. The shape of the calibration function reflects these changes, so in effect production rate of fast neutrons is transparent to the user. We left that paragraph unchanged.

P9 L9 This is only the case where other influences (e.g. biomass) can be neglected.

Response: True. But here we concentrate on soil moisture. We discuss vegetation later in the paper, where we describe the effects of vegetation on the neutron signal. We also included an example that involves vegetation (section 3.4.2). And we added two sentences at the end of this paragraph to indicate importance of other sources of hydrogen. [p. 9, l. 13-15]

P10 L8 The lattice water issue is not very clear to me. How much lattice water can be typically found in soils? Is this a material constant or does its amount change in time? How can the lattice water content be determined? Some more information on how the effect of lattice water should be considered in the calibration should be presented.

Response: Lattice water is water locked in crystal lattice, and as such should be invariant in time (except on time scales relevant to chemical weathering – thousands of years). Typical values are a few percent by weight, but can vary from near zero in quartz to more than 20% in volcanic ash, gypsum and some other hydrated minerals. To illustrate this, we added a table (Table 2) with lattice water values measured at COSMOS sites. We also added text to section 2.4.1 [p. 10, l. 19-24]

Lattice water has the same effect on neutrons as pore water. Since it can be assumed constant in time, we can add it to the pore water measured during calibration, calibrate on the sum of lattice and pore water, and then subtract lattice water when we measure soil moisture using neutrons. The effect is the steepening slope of the calibration function when lattice water is included; thus, the same changes in the neutron intensity will result in greater changes in the computed soil moisture (the range of values of soil moisture at a given site will be expanded). We modified Fig. 6 to show this effect.

P10 L20 An important aspect is the decrease in sensitivity of the CRP with increasing distance. This means that the likelihood that the inferred soil moisture by the CRP corresponds correctly with that of the surrounding soils will sharply decrease with distance. For instance, at our test site we translocated our CRP about 100 m from a hillslope location to a groundwater influenced valley location. Although the wetter zone in the valley was relatively small compared to the footprint size (_10%), the neutron count rate changed and the original calibration estimated at the hillslope location could not predict accurately values of soil moisture at the valley location (Rivera Villarreyes et al., 2011).

Response: Yes, of course this is true as the sensitivity of the probe decreases (approximately exponentially) with the distance. The footprint is the matter of definition. We defined the horizontal footprint as that diameter that contains 86% (2 e-folds, 660 m) of the signal. A different definition could be based on 1-e (64%, 330 m) or 3-e (95%, 990 m). Clearly, this means that heterogeneities of soil moisture at the scale comparable to the footprint will lead to complications. However, soil moisture heterogeneities often display correlation scales of meters to tens of meters, and such heterogeneities are integrated by the probe without serious complications. This potential problem is being researched by our group, but we do not have anything to report at this time.

When a probe is moved to a new location, even a short distance away, it should be calibrated. Rivera Villarreyes et al.'s, 2011 result is not surprising. Essentially they calibrated the probe at one site (with no water table close to the surface), and applied the calibration at another (with water table close to the surface, and thus wetter soils).

P11 L11 Similarly the sensitivity of the CRP will also decrease with depth. This effect should be discussed here in more detail.

Response: The depth sensitivity is an important aspect of the cosmic ray probe. But a detailed discussion of this subject is too long to be included here. Instead, we wrote a separate paper on the subject (Franz et al., 2012a, Water Resour. Res. 48, W08515) and we cite that paper here.

P12 L15 include surface water

Response: Added surface water to new section 2.4.3.

P13 L19-20 From our experience with CRP I would strongly advice not to use a universal function without calibration based on in-situ determined soil moisture in the footprint of the CRP, especially one want to use the data for validation purposes (e.g. remote sensing or model results). The measurement error can easily exceed 100%.

Response: We do not recommend using the universal calibration either; rather, we say that this is the least appropriate way of computing soil moisture from neutron data. However, if calibration cannot be done (e.g., inaccessible location) then universal calibration function is likely better than no calibration. The universal calibration is also the best option for the mobile cosmic-ray probe. Our work on the universal calibration has been described in a separate paper (Franz et al., 2012b, HESSD 9, 10303-10322), which is cited here [p. 10, l. 17-18, p. 11, l. 1-2, 16, p. 14, l. 8, p. 17, l. 17].

P14 L8-9 the accuracy will largely depend on the spatiotemporal variability of the soil moisture and the other hydrogen pools within the CRP footprint.

Response: Possibly. But these effects are still unknown. They depend not only on spatial variations, but also on temporal changes of the spatial variations. Our limited experience suggests the probe integrates the common spatial variations that are at the scale of meters to tens of meters. Much more research will have to be done in future to find out how much uncertainty is added due to spatial variations. At this time we don't know, and we prefer not to go into this subject in this paper.

P14 L9-11 Bogena et al. showed that the vertical weights had a large impact on the footprint averaged soil moisture content. During wet periods, the weight for the top soil in-situ measurements increase to >90%. Since the soil water content also depends on the soil porosity, which normally decreases with depth, a weighting for depth is of great importance. For sites with heterogeneous soil pattern (as described above) also the weighing for distance should be applied.

Response: This is true. For wet soils the top ~10 cm is what the probe sees. For intermediate soils it is 10-20 cm. We described the vertical weights in a paper by Franz et al., 2012 (Water Resour. Res. 48, W08515), cited here [p. 14, l. 30, p. 16, l. 28, p. 28, l. 11.] Similarly large-scale horizontal heterogeneity will have to be addressed by using distance weights, but at this time we do not have data to make statements on the subject.

P15 L13-15 You are only presenting one example, which not sufficient to make such an argument. In our experience, this stability does not exist (see also above). You should undertake a thorough analysis of several other COSMOS sites confirm this statement.

Response: I agree that there is a need to undertake detailed analysis at different sites. But we have only two sites where we have independent soil moisture data at different times, and both sites are in the paper. If in future new data are available, they will add to the database that will allow for broader conclusions to be made. In the meantime we added wordage to indicate that our stability test is at one site only and that more sites need to be studied before a more conclusive statement about stability can be made. [new section 2.6.3]

In addition, we added another example, from a wet climate of Hawaii, to illustrate how the neutron probe responds to frequent rain events when soil is near saturation most of the time. We do not have multiple sets of calibration data, nor do we have a large number of sensors, so we concentrate on pointing out the consistency between neutron signal and precipitation events. We also show time series from a lone TDR profile within 10 m of the COSMOS probe. [section 3.4.3]

P18-21This sections could be shortened in order to reduce redundancy and parts which are too technically (e.g. P19 L25-28).

Response: We agree that the section is quite technical. But this paper describes the network of cosmic-ray probes, and we felt compelled to describe how the data are transmitted. We kept the technical details while removing some redundancies.

References Paper in preparation and presentations should not be cited.

Response: Unpublished papers have been removed. Two papers that were previously listed as “in review” are now published (Franz et al, 2012a, c); these are retained in the paper. A paper on correction for water vapor (Rosolem et al., in preparation) has been removed and a short sentence has been added to describe the correction [p. 21, l. 16-20].

Figures Fig. 5 does not add significant information and thus could be omitted.

Response: Agreed. This figure shows graphically how important hydrogen is. But this information is also presented in Table 1 and Figure 6. Therefore, Figure 5 has been deleted.

Fig. 6 could be reduced to 3 graphs (see above)

Response: As described above, we want to illustrate the importance of hydrogen, particularly at low water contents, so we prefer to keep the zero-water panel.

Fig. 10 could be omitted since it is already presented at the web site

Response: This is the schematic of the probe and its photograph. It is not at any web site that we know (hydroinnova's web page contains different, complementary information), and even if it were, web sites are not permanent nor are they considered publications. We would like to keep the figure (though we do not insist on it).

Fig. 11 does not add significant information and thus could be omitted.

Response: This is the schematic of the COSMOS network. Since the paper is about COSMOS, we think it justified to include this figure (again, we do not insist on it).

Related references

Bogena, H.R., M. Herbst, J.A. Huisman, U. Rosenbaum, A. Weuthen, and H. Vereecken (2010): Potential of wireless sensor networks for measuring soil water content variability. Vadose Zone J., doi:10.2136/vzj2009.0173.

Response: Added this reference and cited it in text.

Vereecken, H., J.A. Huisman, H.R. Bogena, J. Vanderborght, J.A. Vrugt, and J.W. Hopmans. 2008. On the value of soil moisture measurements in vadose zone hydrology. A review. Water Resour. Res. 44. W00D06. doi:10.1029/2008WR006829.

Response: We think that the Bogena et al., 2010 reference on distributed sensor networks is more appropriate here. We included Bogena, but not Vereecken.

Rivera Villarreyes, C.A., H. Bogena, G. Baroni, D. Metzen, and S.E.Oswald. 2011. Cosmic-Ray Neutrons for Estimation of Areal Mean Soil Moisture in Agricultural and Forest Sites. Geophysical Research Abstracts 13, EGU2011-8632

Response: Conference abstracts are discouraged as references. We did not include it.