21GRD08 SoMMet

D4: Good practice guide for calibration practices for CRNS soil moisture data retrieval in outdoor field conditions covering on lateral scales ranging from 10^2 m to 10^3 m and to depths of up to 1 metre

Prepared by: UP DE, UFZ and UNIBO

Organisation name of the lead participant for the deliverable: UP DE

Due date of the deliverable: September 2024

Actual submission date of the deliverable: 30 November 2025

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

Deliverable **D4** of project 21GRD08 SoMMet

Good practice guide for calibration practices for CRNS soil moisture data retrieval in outdoor field conditions covering on lateral scales ranging from 10^2 m to 10^3 m and to depths of up to 1 metre

Authors:
Sascha E. Oswald (UP DE), Gabriele Baroni (UNIBO), Lorenzo Ferlin (UNIBO), Sadra Emamalizadeh (UNIBO) and Martin Schrön (UFZ)

Institutions:
UP DE – University of Potsdam, Germany
UNIBO – University of Bologna, Italy
UFZ – Helmholtz-Centre for Environmental Research, Leipzig, Germany

Glossary

COSMOS: COsmic-ray Soil Moisture Observing System

CRNS: Cosmic-Ray Neutron Sensing

NDVI: Normalized Difference Vegetation Index

PS: Point Scale

SWC: Soil Water Content

TDR: Time Domain Reflectometry

UNIBO: Università di Bologna

WP: Work Package

TABLE OF CONTENTS

Summary

This document, deliverable D4, is the fourth of eight technical deliverables of the project 21GRD08 SoMMet (hereafter: SoMMet). The project has received funding from the European Partnership on Metrology, co-financed by the European Union's Horizon Europe Research and Innovation Programme and by the Participating States (Funder name: European Partnership on Metrology; Funder ID: 10.13039/100019599; Grant number: 21GRD08 SoMMet).

The aim of Task 2.3 "Standardization of the CRNS on-field calibration procedure for soil moisture assessment" of SoMMet has been to review and compare approaches for the soil moisture assessment from the epithermal neutron count rates measured in cosmic-ray neutron sensing (CRNS; also called COSMOS) detectors, as used as methodology for outdoor field-scale observation. As an output of this task, SoMMet provides this good practice guide on calibration procedures for CRNS. This task was strongly linked to Task 2.2 "Validation of existing neutron transport models used to interpret CRNS signals specific to the soil moisture measurand" of SoMMet because the environmental systematic influences that affect the CRNS footprint and the resulting soil moisture assessment, play a role here.

This SoMMet deliverable closes with recommendations for users (see Section 2.6) as a central component to constitute a good practice guide. This is partly based on works within SoMMet, as exemplarily also shown here, but also influenced by work of the authors in other projects and general discussion in the CRNS community.

1. Introduction and context

1.1 General introduction

The application of stationary CRNS to obtain soil moisture time-series of a particular location requires three major steps.

1. Installing a CRNS device at the site including a suited set-up and ensuring its continued operation including data storage and potentially remote data transmission. The main data set consists of the epithermal counts for individual times and periods of accumulating counts, accompanied by meteo-data (which alternatively could be taken from a separate meteo-station). Additional info on detector-specific counting parameters, e.g., pulse height and length spectra, is optional and may be useful for diagnostic purposes.
2. Processing of raw data to remove false data and outliers, to identify periods of snow, and to apply physical signal corrections methods, eventually providing a time series of cleaned, corrected neutron count rates.
3. Convert the cleaned, corrected neutron count rates into a soil moisture time series for the site. This requires site specific information. Exact procedures prescribe taking such data during operation of the CRNS station and include independent soil moisture measurements, while reasonable estimates may also be achieved from supporting knowledge about the detector and site characteristics.
   This step is called “calibration” and should be done at least once during the CRNS station is operated at the site. The resulting calibration parameter can be used for soil moisture conversion with all previous and future CRNS data at the particular site.

The application of CRNS in mobile form, so called CRNS roving, be done by car [Desilets et al., 2010; Schrön et al., 2018], train [Schrön et al., 2021; Altdorff et al., 2023], trolley [e.g., Fersch et al., 2020] or even as backpack, is not covered by this good practice guide.

1.2 Context and Standard

The first step is specific to the CRNS device, as there are different brands, detector materials, sizes, weights, shapes, and electronics involved depending on the manufacturer. Thus, users should follow the instruction of the particular device manual provided by the manufacturer. However, it should be clear that a stationary CRNS is an above-ground measurement. Common to all is a height above ground for the detector that should be within 1.5 to 2.0 m.

In a recent initiative for the first time a community standard for CRNS is outlined. Also, some SoMMet partners have contributed to this. Following the idea of a global community-driven standard, we refer to this document (Schrön et al., 2025) for the basics of CRNS data processing addressing mainly step 2 from above. Step 3, the calibration procedure, is complex, site-dependent, and subject of research, going much beyond the COSMOS Reference document. SoMMet has contributed to a better understanding of this calibration procedure, so that it will be the subject of the following sections.

2. Calibration approaches

2.1 Introduction to calibration approaches

The CRNS calibration process is one of three key components for the use of CRNS in environmental monitoring (see above). Corrected neutron count rates must be provided in a previous step, to account for at least air pressure changes and neutron incoming variability, and in forest also for the background by biomass. In order to convert to soil water content (SWC), a transfer function needs to be adopted to precisely quantify the target variable. It should be noted SWC can be a gravimetric water content or a volumetric water content, see the *Global COSMOS Reference* document (Schrön et al., 2025).

The first conversion function proposed in literature for SWC estimation is the so-called Desilets equation (Desilets et al., 2010). We refer here to the *Gobal COSMOS Reference* document, Chapter 11 (“Conversion to soil moisture”, and the function(s) set as standard currently). Essential, for calculation of gravimetric soil moisture is a single calibration factor, N_0 (or alternatively N'_{max} = 1.0746 N_0). Further, alternative approaches have been outlined in Oswald (2025). To obtain SWC, it is necessary to account for the actual soil conditions in the field, as they can influence the CRNS signal. Most importantly, information is required about soil bulk density, the water equivalent of lattice water (mineral bound water in soil), and the water equivalent of organic matter content in soil.

CRNS measurements are typically relative, hence, the determination of a calibration parameter N_0 is required for precise quantification of SWC for the whole CRNS time series. To determine N_0, best most accurate approach requires knowledge of corrected neutron count rate *N* and the independently measured SWC around the sensor at the same time. There are modern software tools to support this procedure (e.g., https://www.neptoon.org/), including the processing from raw CRNS data via calibration and conversion to SWC time series. The details of this calibration step are reviewed in the following.

2.2 Current calibration approaches

The calibration narrows down to the need of estimating a representative SWC as an absolute value. The current best practice is to achieve that by a so-called local calibration as described as follows.

Once the installation of the CRNS is performed, a number of sampling locations can be selected to represent the area-average soil moisture value as seen by the CRNS (two suggestions are shown in Figure 1). Franz et al. (2012) proposed 18 locations in three distances and 60° apart from each other as a pragmatic approach (Figure 1a). Schrön et al. (2017) suggested adaption of these distances based on the general wetness condition at the site, weighting of the samples by distance in post-processing, and particular focus on samples in the first few meters around the detector where it is most sensitive to. At each location, soil samples at different depths should be collected and weighted by depth to account for the higher neutron sensitivity to shallow soil. As far as possible, the undisturbed soil samples are collected down to 30 or 40 cm at 5 cm intervals. Alternative to sampling also point scale sensors could be used instead.

The suggested weighting approaches based on distance from the sensor and soil depth were based on data from homogeneous sites with circular footprints. While this shows to better represent typical footprint characteristics, the adaptation of the location based on actual soil moisture is difficult due to the need to know a priori average SWC values. In some cases, site heterogeneity can strongly vary, and the terrain could be complex, such that individual sampling schemes can be used for determining the area- and depth-average soil moisture. An interactive online tool has been developed, also by SoMMet, to support decision-making for soil sample designs in complex terrain: https://neptoon-tools.streamlit.app/Vertical_averaging.

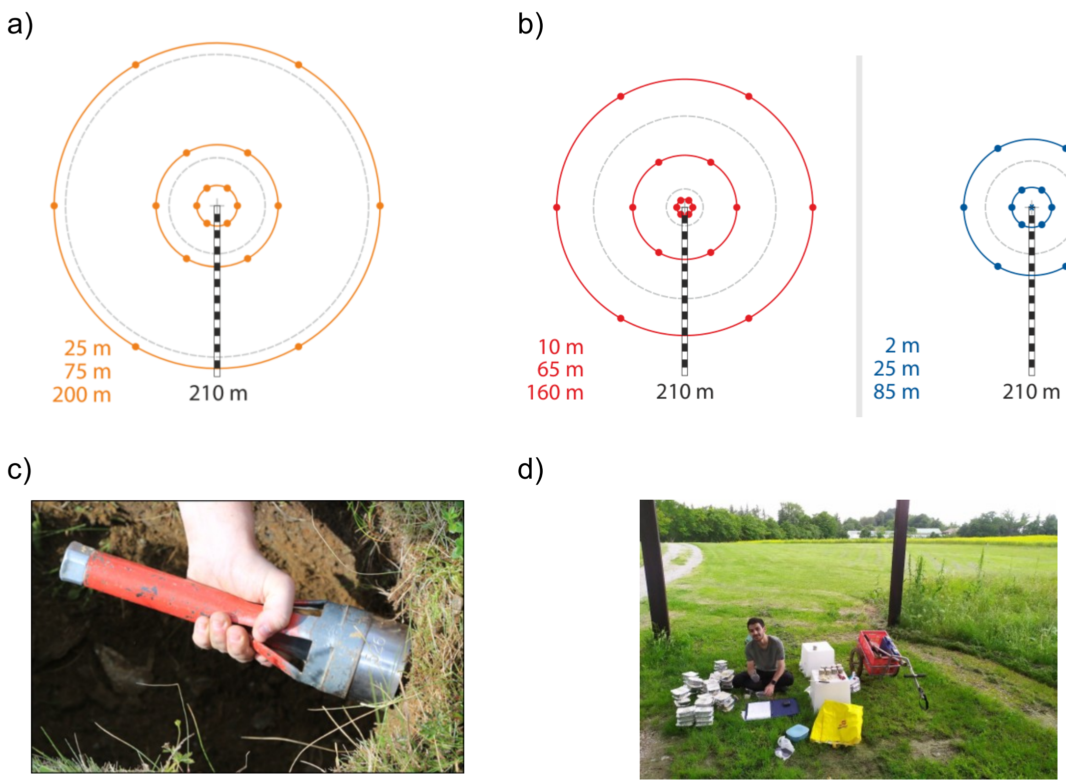

Figure 1. Originally proposed sampling scheme at different distances and angles from CRNS station (a), and two possible design suggestions for sampling locations (b) based on neutron transport modelling at a "rather dry" (red) and "rather wet" (blue) site (see Schrön et al., 2017). Fieldwork photos conducted by UNIBO: taking a soil sample at particular depth (c) and general equipment (d).

Finally, a subset of soil samples can be used to measure (average) soil organic carbon and lattice water (e.g., Barbosa et al., 2021; Scheiffele et al., 2020) to account for additional hydrogen pools.

While a single calibration should be sufficient for CRNS calibration, three soil surveys conducted possibly under distinct soil moisture conditions have also been suggested (Heidbüchel et al., 2016; Iwema et al., 2021).

2.3 Possible alternatives in literature

Such a local calibration as described in 2.2 may be difficult or impractical, for example when soil contains stones, in presence of bedrock outcrops, in urban environments, or when no such campaign could be done while the CRNS station is operating, or when it stopped before such a campaign. For this reason, some alternatives have been proposed.

Franz et al. (2013) suggested a universal calibration function for determination of soil moisture with cosmic-ray neutrons. The new function explicitly takes into account all the hydrogen pools with the hypothesis that the local calibration is no needed anymore. The proposed method requires, however, ancillary data that are not always available and so far, this approach has not been widely applied.

Andreasen et al. (2020) suggested the use of neutron transport simulations to overcome the need of local calibration. The methodology faced some challenges in complex environment like forest and the users should have a good knowledge of neutron transport simulations and modelling. So far, also this approach is not commonly applied for calibration as often not being viable in practice.

Finally, an alternative approach has been recently proposed by (Heistermann et al., 2024) where the N_0 or N'_{max} parameter is calculated site-specific by a "general calibration function". This function is based on site-specific information such as altitude, geomagnetic location, soil bulk density plus the sensitivity of the particular CRNS detector installed. The sensitivity is defined as its count rate relative to the count rate of a reference detector. If possible, site data should also include average lattice water content and organic matter content in soil. In this way it becomes *independent from local SWC measurements* and related errors and spatial variability due to not applying a local calibration in respect to SWC. Instead, it takes into account all the main factors that influence the local neutron intensity level to provide an estimate of N_0 or N'_{max}, for example when not enough trustworthy local SWC values measured during operation of the CRNS station are available yet or will not become available. An interactive online tool has also been provided to support this procedure (https://cosmic-sense.github.io/local-or-global/).

2.4 Possible alternatives explored within the SoMMet project

Beyond the review as above, we have discussed alternative approaches within the SoMMet project. One reasoning is that local information is needed (though not necessarily SWC), but the number of sampling locations for a local calibration is debatable, locally dependent and could be optimized. Some own results have been obtained also, and one example is given in the following test approach.

2.4.1 Example: Field test to assess number of locations for CRNS calibration

As previously discussed, a set of 18 locations has been proposed to quantify the average SWC across the CRNS footprint. This number can be, however, matter of discussion. On the one hand, the 18 locations may not represent well the soil variability and the SWC observations could introduced an error in the calibration. On the other hand, specific locations might be more informative for estimating the areal average (Vachaud et al., 1985).

We explore these issues by analysing surface SWC acquired with a portable TDR during some field campaigns at the Bondeno site, Italy (Figure 2). The whole field has a size of about 56 hectares and is described in the following, with the area where CRNS station is installed marked in green.

Based on this data set, average SWC is estimated by sub-sampling the full datasets with combination of lower number of samples. Preliminary results are shown as example in Figure 3. The results suggest that reducing the number of locations from 24 initial points to 12 is a practice that did not affect too much the average SWC. The same cannot always be confirmed reducing the number further to 8 or 4 sampling points. This drawback opens the issue that for some combination of four representative points chosen, and for some agricultural fields, the calibration optimization can be acceptable while for others it’s quite not representative.

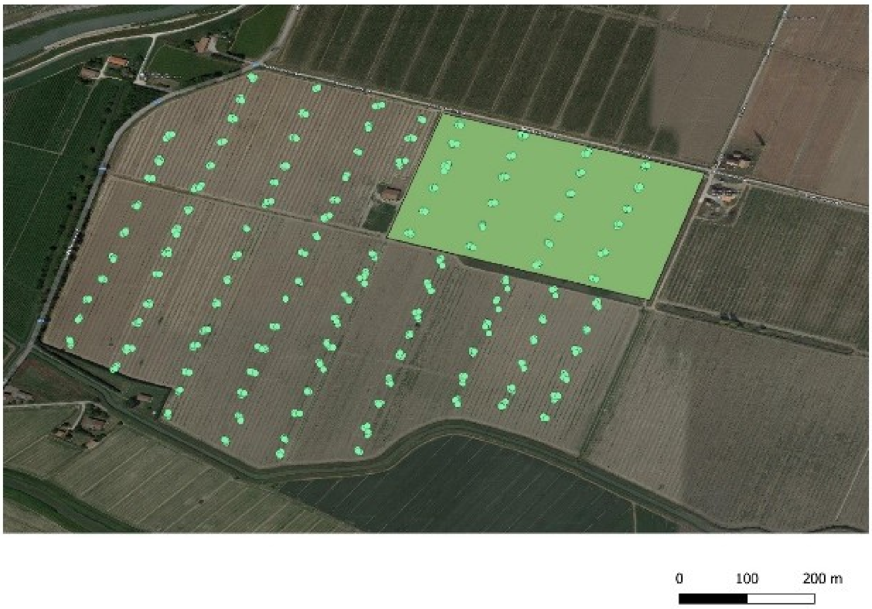

Figure 2. Bondeno agricultural field with TDR surveys. CRNS located on the topright area, marked in green. Positions are marked where surface SWC was measured in field campaigns.

Indeed, a general rule for optimum calibration in any agricultural field could not be achieved, and this should be similar for grassland or forest. A possible way would be to first conduct a full soil sampling campaign. This would help to understand the field zones where it would be better to acquire a soil sample during a calibration to have a more precise soil moisture representativeness. This process can be useful also to recalibrate the CRNS station.

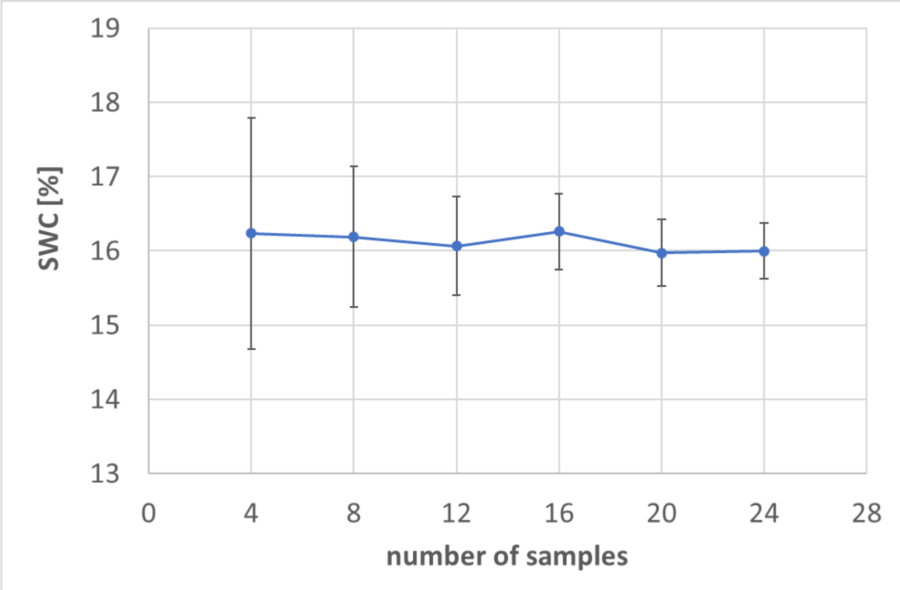

Figure 3. SWC for the 5th of April 2023 TDR campaign at the Bondeno site by using subsamples of the data set. Left to right is decreasing numbers of samples used.

2.4.2 Example: The use of secondary information to optimize sampling location

A second approach can be connected to the usage of other information regarding the field such as vegetation indices from remote sensing. As one example, NDVI (Normalized Difference Vegetation Index) maps describing the spatial variability and mainly used to assess agricultural productivity can for instance be adopted for the assessment of the spatial variability and supporting sampling optimization (Figure 4). Preliminary analysis shows however, that the acquisition time strongly affect the zonation and might influence the optimization accordingly.

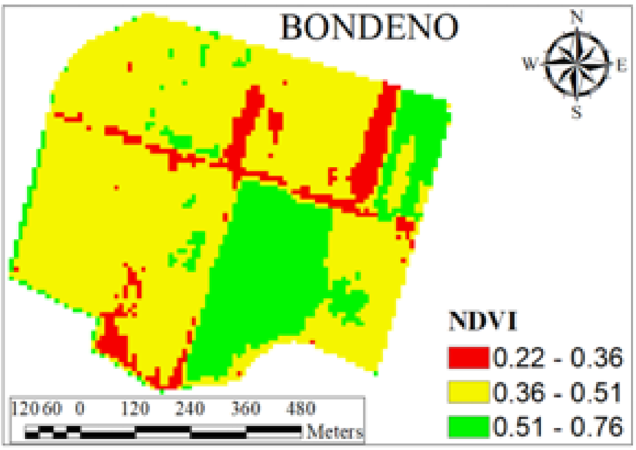

Figure 4. Maps of NDVI at Bondeno (on 17th June 2023).

Approaches like this could also work with other geophysical data, such as land use. Schrön et al. (2017) have suggested to average all samples within the same land use class and then weight those zones depending on their distance to the sensor (Figure 5). The current global COSMOS Reference document suggests assigning samples to predefined annuli and work with a sample-based average for each annulus but does not require to follow this procedure.

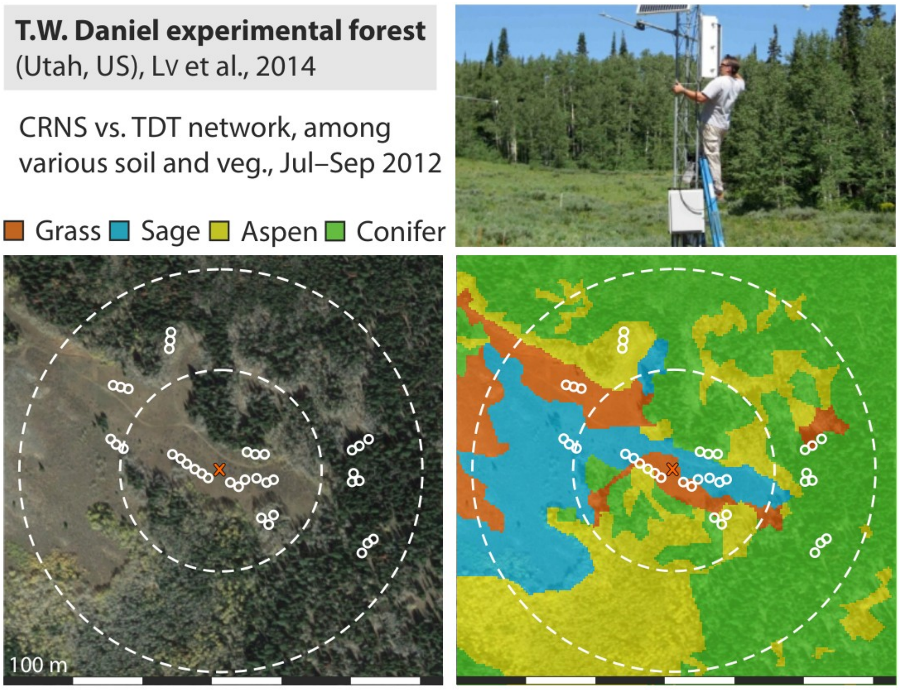

Figure 5. Example of zonal weighting of existing soil sample profiles based on a land use map according to Schrön et al. (2017).

2.5 Conclusions on state-of-the-art

2.5.1 Conclusions on calibration approaches

Based on these preliminary analyses, the following considerations are drawn.

Despite some effort in literature to avoid the need of local calibration, some soil information seems to be necessary. The current approach of 18 sampling locations and soil samples down to 30 cm (or 40 cm) is not a common standard and arguably has some disadvantages. These are, for example, the high practical effort (108 or 144 samples from defined depth positions down to 30 or 40 cm, respectively), which in some cases still may be not enough to provide full representation of the inner part of the footprint when taking the current estimates of its shape (Schrön et al., 2017) and potentially not covering the full horizontal variability within the footprint.

Moreover, a particular number of pre-defined soil sample locations seems to be difficult to rectify. This also challenges the use of exactly 18 locations as a standard protocol.

The use of a first intensive soil sampling acquisition seems to be needed to have a trustworthy calibration. An additional calibration campaign could be adopted based on this. Specifically, a solution can be to have a standard calibration approach always acquiring 18/24 initial points around the CRNS station to be later processed in the laboratory to have a general idea about SWC. Once this first soil samples acquisition is done, the number of locations could be reduced for subsequent calibration designs, if desired.

The use of vegetation indices is promising but the effect of agricultural practices could limit the definition of zones. In any case, an additional analysis on every experimental agricultural field can be useful for more precise further evaluations.

2.5.2 Conclusions on area represented

How to define the footprint (i.e. support volume) has been initiated by Desilets and Zreda (2013), which is essentially the widely used definition today. The current formulation in Schrön et al. (2025) suggests that the footprint radius is defined as "the distance within which 86 % of the *measured* neutrons first probed the soil". And the vertical extent of the footprint is usually defined in an analogous way, see next section. For its horizontal extent formulas assuming such a circular symmetry have been developed under homogenous reference conditions (see Köhli et al., 2015, Schrön et al., 2017). Nevertheless, these formulas do not apply for strongly heterogenous soil moisture distribution in the area. Furthermore, they are not applicable for cases of extremely low soil bulk density, where the vertical averaging depth (D_{86}) could be much different than expected by the current formula (cf. Chapter 14 in Schrön et al. (2025)). Finally, the existing footprint definition is not taking into account intermediate interactions of neutrons with the soil between first probing the soil and detection. Thus, it can be expected that there will be more work needed to either remove these drawbacks of this footprint definition or establish other ones. Also, a more pragmatic handling of the area represented by a CRNS observation, as suggested by Oswald (2025), could ease efforts, at least for low-level application of CRNS (see tier level 1 below).

The vertical footprint, that is the integration depth D_{86} from soil surface downwards from which most of the signal results (again set as 86 % percent), is varying with SWC to some degree, similar to other non-invasive methods. Also, it has a substantial inherent weighting, as is the case for the horizontal footprint also, decreasing exponentially with depth below soil surface. This could be compensated for in the evaluation by using approaches to unweight this depth-weighted SWV, for example based on soil profile measurements (or modelling), via the approach by Scheiffele et al. (2020) or other future ones.

For soils with very low or very high soil bulk density the current formula for the integration depth D_{86} is not recommended to be used (Schrön et al., 2025). It could be applied to provide a first estimate of the footprint depth, but since porosity affects CRNS measurement depth, only a modified or new (validated) approach will be able to provide exact numbers of D_{86} for these special conditions in the future.

2.6 Recommendation for users

We suggest offering three tiers ("quality levels") of calibration approaches, where users can decide which tier level they chose depending on their capabilities, data availability, and other circumstances. We number the tier levels from the lowest quality level (1) to the highest quality level (3).

2.6.1 Tier 1 (Applied user / preliminary scientific calibration)

a. **Calibration**: General calibration (Heistermann et al., 2024) or equivalent approach. Accounting at least for altitude, CRNS detector sensitivity, geomagnetic location, (mean) soil bulk density. These values may be derived from maps and not necessarily from direct (current) measurements at the site.
b. **Horizontal footprint size**: Place the CRNS station at a location within the area of interest, which should at least span over a radius of 50 m around the CRNS station. The area should be similar in conditions, especially in land use, terrain and soil properties, and shall not include larger water bodies or buildings. A typical area represented is a cropped field or a piece of forest with a CRNS station in its centre; also, placing the CRNS in a pathway between two similar agricultural fields is an option to represent the two fields together. Take the derived SWC as representing the whole area as a (arithmetic) mean value.
c. **Vertical footprint size**: Take the derived SWC as representing *root zone soil moisture*, that is deeper than surface soil moisture, shallower than the whole soil water storage, and typically covering a few decimetres. The naming is rather indicative and relates to covering by its definition a major part of the soil moisture storage directly accessible by shallow root systems (grass, crops). Be aware it is inherently weighted towards the surface.
d. **Other hydrogen pools**: Ignore. But if the site is in a (dense) forest apply a constant biomass correction based on biomass estimate (not necessarily from direct (current) measurements at the site), see Bogena et al. (2022) or Heistermann et al. (2024). The biomass correction factor is roughly 0.9 (i.e., 10 % less) on the neutron count rates for typical central European forests. If it is a particularly clay-rich soil or rich of organic carbon, subtract ~0.10 m^3/m^3 from the CRNS soil moisture product.

Absolute value of soil moisture will not be accurate. SWC dynamics should be reasonable. Typically, daily values.

2.6.2 Tier 2 (Basic scientific / basic CRNS network or cluster calibration)

a. **Calibration**: Large number of point sensor measurements at 12-18 locations including 6-9 depth profiles (down to at least 30 cm). Account for distance to CRNS station and apply horizontal weighting (according to Schrön et al. (2017); alternatively use the annulus ring approach described there, where an explicit weighting is not needed as it is implicitly included in the design of the 18 sampling points). Focus particularly on locations near the detector and close to the surface. Alternative: General calibration with detailed local information also on lattice water, organic carbon content, profile of soil bulk density.
b. **Horizontal footprint size**: It can be assumed to be fixed. Use 200 m radius for a generally dry site (with low field capacity), 150 m for a medium moist site (with medium field capacity) and 110 m for an overall wet site (e.g. wetlands). In dense forests, the footprint can even shrink to 50 m. Note that these values are a pragmatic choice based on Schrön et al. (2025) and corresponding literature (and a mean air humidity).
c. **Vertical footprint size**: Use a soil moisture profile measurement (or several). Apply the Scheiffele et al. (2020) approach to obtain an unweighted SWC that represents (even) root-zone soil moisture. Essentially, a mean SWC from the soil moisture profile over a CRNS-

weighted SWC from the soil moisture profile is used to determine a shape correction factor f_{pc}; this (usually time-dependent) factor then has to be multiplied by the CRNS derived SWC to derive an unweighted SWC time series.

d. **Other hydrogen pools**: Some info on lattice water, organic carbon content, estimate of above ground biomass (constant). If forest, (constant) biomass correction to be applied, based on local estimate of above ground biomass.

Sub-daily values possible; typical: 6 h (for detectors with ~2000 cph) to 12 h (for detectors with ~1000 cph) with moving average of 12 h (left and right).

2.6.3 Tier 3 (Advanced scientific calibration/high-end CRNS network or cluster calibration)

a. **Calibration:** Large number (at >= 18 locations including >=9 depth profiles down to at least 30 cm) of gravimetric soil moisture measurements or point sensor network with calibration to local soil conditions, best by gravimetric samples; including profile information for soil moisture and bulk density. Account for distance to CRNS station and apply horizontal and vertical weighting (according to Schrön et al. (2017)). Take particular care for the area near the CRNS and for shallow depths.
b. **Horizontal footprint size**: Varying footprint radius based on the most recent COSMOS Reference document.
c. **Vertical footprint size**: Time-dependent calculation of integration depth based on SWC of that time step (as an iterative process) and profile shape information from at least one measurement. SoMMet has produced interactive online tools to support vertical weighting of soil moisture data even for TDR time series: https://neptoon-tools.streamlit.app/Vertical_averaging. If an unweighted SWC is desired, use Scheiffele et al. (2020) approach (see Tier 2 above).
d. **Other hydrogen pools**: Local measurements on lattice water, organic carbon content, above ground biomass (time-dependent for larger crops), possibly including vegetation structure and below ground biomass. If forest, biomass correction based on local measurements to be applied, being time-variant if there are indications for this to be relevant (e.g., forest clearings or reforestation during longer time series).

Large sensitivity of CRNS detector may allow to obtain hourly values without too much noise (by detectors with ~6000 cph or more) rather than 6-hourly values (for detectors with ~2000 cph); still some smoothing (moving average) will be necessary.

Using more than one calibration campaign, at different soil moisture conditions, is favourable to obtain an accurate value of the calibration parameter.

3. References

Altdorff, D., S. E. Oswald, S. Zacharias, C. Zengerle, P. Dietrich, H. Mollenhauer, S. Attinger and M. Schrön, 2023. Toward Large-Scale Soil Moisture Monitoring using Rail-based Cosmic Ray Neutron Sensing, Water Resources Research, 59(3), e2022WR033514, https://dx.doi.org/10.1029/2022WR033514.

Andreasen, M., Jensen, K.H., Bogena, H., Desilets, D., Zreda, M., Looms, M.C., 2020. Cosmic Ray Neutron Soil Moisture Estimation Using Physically Based Site-Specific Conversion Functions. Water Resour. Res. 56, e2019WR026588. https://doi.org/10.1029/2019WR026588.

Barbosa, L.R., Coelho, V.H.R., Scheiffele, L.M., Baroni, G., Filho, G.M.R., Montenegro, S.M.G.L., Almeida, C. das N., Oswald, S.E., 2021. Dynamic groundwater recharge simulations based on cosmic-ray neutron sensing in a tropical wet experimental basin. Vadose Zone J. 20, e20145. https://doi.org/10.1002/vzj2.20145.

Bogena, H.R., Martin Schrön,, Jannis Jakobi, Patrizia Ney, Steffen Zacharias, Mie Andreasen, Roland Baatz, David Boorman, Mustafa Berk Duygu, Miguel Angel Eguibar-Galán, Benjamin Fersch, Till Franke, Josie Geris, María González Sanchis, Yann Kerr, Tobias Korf, Zalalem Mengistu, Arnaud Mialon, Paolo Nasta, Jerzy Nitychoruk, Vassilios Pisinaras, Daniel Rasche, Rafael Rosolem, Hami Said, Paul Schattan, Marek Zreda, Stefan Achleitner, Eduardo Albentosa-Hernández, Zuhal Akyürek, Theresa Blume, Antonio del Campo, Davide Canone, Katya Dimitrova-Petrova, John G. Evans, Stefano Ferraris, Félix Frances, Davide Gisolo, Andreas Güntner, Frank Herrmann, Joost Iwema, Karsten H. Jensen, Harald Kunstmann, Antonio Lidón, Majken Caroline Looms, Sascha Oswald, Andreas Panagopoulos, Amol Patil, Daniel Power, Corinna Rebmann, Nunzio Romano, Lena Scheiffele, Sonia Seneviratne, Georg Weltin, and Harry Vereecken, 2022: A European Network of Cosmic-Ray Neutron Soil Moisture Sensors, Earth Syst. Sci. Data, 14, 1125–1151, https://doi.org/10.5194/essd-14-1125-2022.

Desilets, D., M. Zreda, and T. P. A. Ferré (2010). “Nature’s neutron probe: Land surface hydrology at an elusive scale with cosmic rays”. In: Water Resources Research 46(11). DOI: 10.1029/2009WR008726.

Desilets, D. and Zreda M. (2013). Footprint diameter for a cosmic-ray soil moisture probe: Theory and Monte Carlo simulations, Water Resources Research 49(3566), https://doi.org/10.1002/wrcr.20187.

Fersch, B., Francke, T., Heistermann, M., Schrön, M., Döpper, V., Jakobi, J., Baroni, G., Blume, T., Bogena, H., Budach, C., Gränzig, T., Förster, M., Güntner, A., Hendricks-Franssen, H.-J., Kasner, M., Köhli, M., Kleinschmit, B., Kunstmann, H., Patil, A., Rasche, D., Scheiffele, L., Schmidt, U., Szulc-Seyfried, S., Weimar, J., Zacharias, S., Zreda, M., Heber, B., Kiese, R., Mares, V., Mollenhauer, H., Völksch, I., and Oswald, S., 2020: A dense network of cosmic-ray neutron sensors for soil moisture observation in a pre-alpine headwater catchment in Germany, Earth Syst. Sci. Data, 12, 2289–2309, https://doi.org/10.5194/essd-12-2289-2020.

Franz, T.E., Zreda, M., Rosolem, R., Ferre, T. p. a., 2012. Field Validation of a Cosmic-Ray Neutron Sensor Using a Distributed Sensor Network. Vadose Zone J. 11, vzj2012.0046. https://doi.org/10.2136/vzj2012.0046.

Franz, Trenton E., 2012 Installation and calibration of the cosmic-ray, Feb. 2012, solar moisture probe, https://www.hydroinnova.com/_downloads/Trenton_field_guide.pdf, accessed 01/08/2025.

Franz, T.E., Zreda, M., Rosolem, R., Ferre, T.P.A., 2013. A universal calibration function for determination of soil moisture with cosmic-ray neutrons. Hydrol. Earth Syst. Sci. 17, 453–460. https://doi.org/10.5194/hess-17-453-2013.

Heidbüchel, I., Güntner, A., Blume, T., 2016. Use of cosmic-ray neutron sensors for soil moisture monitoring in forests. Hydrol. Earth Syst. Sci. 20, 1269–1288. https://doi.org/10.5194/hess-20-1269-2016.

Heistermann, M., Francke, T., Schrön, M., Oswald S.E., 2021. Spatio-temporal soil moisture retrieval at the catchment-scale using a dense network of cosmic-ray neutron sensors, Hydrol. Earth Syst. Sci., 25, 4807–4824, https://doi.org/10.5194/hess-25-4807-2021.

Heistermann, M., Francke, T., Schrön, M., Oswald, S.E., 2024. Technical Note: Revisiting the general calibration of cosmic-ray neutron sensors to estimate soil water content. Hydrol. Earth Syst. Sci. 28, 989–1000. https://doi.org/10.5194/hess-28-989-2024.

Iwema, J., Schrön, M., Koltermann Da Silva, J., Schweiser De Paiva Lopes, R., Rosolem, R., 2021. Accuracy and precision of the cosmic-ray neutron sensor for soil moisture estimation at humid environments. Hydrol. Process. 35, e14419. https://doi.org/10.1002/hyp.14419.

Köhli, M., Weimar, J., Schrön, M., Baatz, R., Schmidt, U., 2021. Soil Moisture and Air Humidity Dependence of the Above-Ground Cosmic-Ray Neutron Intensity. Front. Water 2, 544847. https://doi.org/10.3389/frwa.2020.544847.

McJannet, D. L. and Desilets, D. (2023). Incoming Neutron Flux Corrections for Cosmic-Ray Soil and Snow Sensors Using the Global Neutron Monitor Network, Water Resour. Res., 59, e2022WR033889, https://doi.org/10.1029/2022WR033889.

Oswald, S.E., 2025. Technical note: Towards a paradigm change in observing soil water content via cosmic-ray neutron sensing, preprint, https://doi.org/10.5194/egusphere-2024-4141, 2025.

Scheiffele, L.M., Baroni, G., Franz, T.E., Jakobi, J., Oswald, S.E., 2020. A profile shape correction to reduce the vertical sensitivity of cosmic-ray neutron sensing of soil moisture. Vadose Zone J. 19, e20083. https://doi.org/10.1002/vzj2.20083.

Schrön, M., Köhli, M., Scheiffele, L., Iwema, J., Bogena, H.R., Lv, L., Martini, E., Baroni, G., Rosolem, R., Weimar, J., Mai, J., Cuntz, M., Rebmann, C., Oswald, S.E., Dietrich, P., Schmidt, U., Zacharias, S., 2017. Improving calibration and validation of cosmic-ray neutron sensors in the light of spatial sensitivity. Hydrol Earth Syst Sci 21, 5009–5030. https://doi.org/10.5194/hess-21-5009-2017.

Schrön, M., R. Rosolem, M. Köhli, L. Piussi, I. Schröter, J. Iwema, S. Kögler, S. E. Oswald, U. Wollschläger, L. Samaniego, P. Dietrich, S. Zacharias, 2018. Cosmic-Ray Neutron Rover Surveys of Field Soil Moisture and the Influence of Roads, Water Resources Research, WRCR23381, 54(9), 6441-6459, doi:10.1029/2017WR021719.

Schrön, M., S. E. Oswald, S. Zacharias, M. Kasner, P. Dietrich, S. Attinger, 2021. Neutrons on Rails - trans-regional monitoring of soil water content and snow, Geophysical Research Letters; 48(24), e2021GL093924. https://doi.org/10.1029/2021GL093924.

Schrön, M., Zacharias, S., Baatz, R., Baroni, G., Bogena, H., Brogi, C., Fersch, B., Franz, T., Hertle, L., McJannet, D., Oswald, S., Power, D., Rasche, D., Rosolem, R., & Global COSMOS Consortium, 2025. Global COSMOS Reference. Zenodo. https://doi.org/10.5281/zenodo.17959505.

Vachaud, G., Passerat De Silans, A., Balabanis, P., Vauclin, M., 1985. Temporal Stability of Spatially Measured Soil Water Probability Density Function1. Soil Sci. Soc. Am. J. 49, 822. https://doi.org/10.2136/sssaj1985.03615995004900040006x.