Neutrons on Rails – trans-regional monitoring of soil moisture and snow water equivalent

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Key Points:

- Cosmic-ray neutron detectors in trains respond to spatial patterns of water content.
- First experiments and analysis provide a proof of concept.
- Using the railway system for regular environmental monitoring could extend the measurement capability to trans-regional and nationwide scales.

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Abstract

Large-scale measurements of the spatial distribution of water content in soils and snow are challenging for state-of-the-art hydrogeophysical methods. Cosmic-ray neutron sensing (CRNS) is a non-invasive technology that has the potential to bridge the scale gap between conventional in-situ sensors and remote-sensing products in both, horizontal and vertical domains. In this study we explore the feasibility and potential of estimating water content in soils and snow with neutron detectors in moving trains. Theoretical considerations quantify the stochastic measurement uncertainty as a function of water content, altitude, resolution, and detector efficiency. Numerical experiments demonstrate that the sensitivity of measured water content is almost unperturbed by train materials. And finally three distinct real world experiments provide a proof of concept on short and long-range tracks. With our results a trans-regional observational soil moisture product becomes a realistic vision within the next years.

Plain Language Summary

Large-scale measurements of the spatial distribution of water content in soils and snow are challenging for state-of-the-art hydrogeophysical methods. Cosmic-ray neutron sensing (CRNS) is a mobile and non-invasive technology that has the potential to bridge the scale gap between conventional in-situ sensors and satellite measurements in both, the horizontal and the vertical domain. In this study we explore the feasibility and potential of estimating water content in soils or snow with neutron detectors in trains. Theoretical considerations estimate how train velocity and recording period influence the uncertainty of such measurements and demonstrate that train materials hardly affect the neutron response to water content. Three distinct experiments provide a proof of concept on short and long-range tracks. With our results a trans-regional observational soil moisture product becomes a realistic vision within the next years.

1 Introduction

Water stored in soils and snow controls the energy and water exchange between the terrestrial surface and the atmosphere (Vogel et al., 2018), impacts regional weather, and shapes the development of hydrometeorological extremes like heat waves, droughts, floods, or avalanches (e.g., Lehning et al., 1999; Douville & Chauvin, 2000; Liang & Yuan, 2021). Therefore, a solid estimation of land surface water at relevant spatiotemporal scales is of utmost importance.

Satellite-based remote sensing platforms aim at global estimations of water in soils and snow at resolutions of several kilometers with the prospect of finer resolutions using new instrumentation and algorithms (Chan et al., 2016; Mattia et al., 2018; Foucras et al., 2020). However, major limitations are the shallow measurement depth (∼cm), long return frequencies (∼days), and low performance during complex weather conditions, under vegetation cover, and in complex terrain (Fang & Lakshmi, 2014; Lawford, 2014). Ground-based in-situ sensors have been developed to measure water content in different soil depths with high spatiotemporal precision and extent from the point to smaller field scales (Bogena et al., 2010; Romano, 2014; Ochsner et al., 2013; Dorigo et al., 2021). However, the sensors require regular maintenance, the spatial representativity is low (∼m), and the concept is not scalable to regional scales (Pan & Peters-Lidard, 2008; Schelle et al., 2013).

The critical scale gap between in-situ and remote sensing techniques could be closed by Cosmic-Ray Neutron Sensing (CRNS) (Zreda et al., 2012; Andreasen et al., 2017). The proximal sensing technique is based on the passive and non-invasive detection of cosmic-ray neutrons. Their intensity strongly depends on the hydrogen abundance in the surrounding environment and thereby responds to water. According to Köhli et al. (2015), the signal intrinsically covers large areas (∼15 ha) and soil depths (∼10–70 cm), making it a "fundamental breakthrough … in the monitoring … of soil moisture status" (Romano, 2014). Stationary CRNS has been successfully applied in research, agriculture, and water resource management, usually at single locations, sometimes integrated in small or national networks (Evans et al., 2016; Andreasen et al., 2017; Fersch et al., 2020). To overcome this spatial limitation, the detector can be used in a mobile mode similar to the so-called car-borne CRNS rover. This mobile variant can capture spatially resolved information of root-zone soil moisture (or snow) from the field to catchment scale *en pas-*

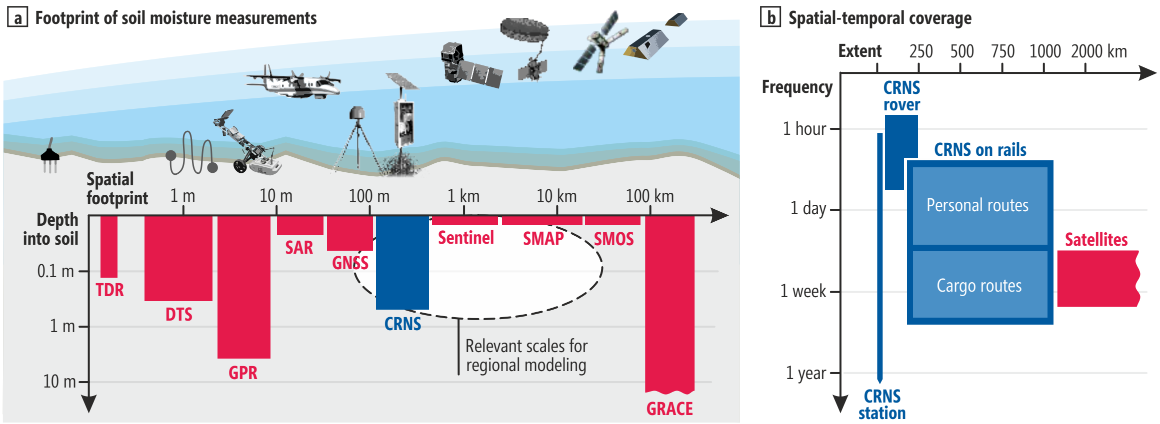

Figure 1. CRNS on rails may close the gap for soil moisture products at relevant scales. (a) Horizontal and vertical footprint of soil moisture measurement techniques (log scale). (b) Spatial and temporal extent of stationary CRNS, mobile CRNS, and satellite systems.

sant (Dong et al., 2014; McJannet et al., 2014; Schrön, Rosolem, et al., 2018; Fersch et al., 2018; Vather et al., 2019). However, this car-borne CRNS roving is a demanding method in terms of personnel and time constraints. A monitoring concept to support a trans-regional observational product would require significantly larger scales and more frequent measurements (see Fig. 1). One option for a new mobile platform is the use of existing transport infrastructure, such as public or cargo transportation (buses, trucks, or trains).

While railway infrastructure is already attracting some interest in the field of applied geophysics (Lavoué et al., 2021; Ižvolt et al., 2016), the present feasibility study specifically pushes the current limitation of mobile CRNS towards trans-regional monitoring. We will begin with theoretical considerations about the expected measurement uncertainty and spatial resolution, followed by a sensitivity study on the influence of vehicles and track beds using numerical simulations. We will then showcase three experiments in real trains to demonstrate the feasibility of train-based CRNS roving to trans-regionally monitor water content of soils and snow.

2 Basic considerations on the general feasibility

The CRNS method relies on the detection of the natural neutron radiation in the energy range of 1–1000 eV. The key features of this method are:

- neutrons are mostly insensitive to most materials other than hydrogen (Zreda et al., 2012),
- the detector receives signals from all directions, integrating over a footprint area of $\sim$ 100–300 m radius (Köhli et al., 2015),
- neutron intensity provides information regarding soil moisture from depths of up to 70 cm (Franz et al., 2013; Köhli et al., 2015).

CRNS detectors usually consist of shielded proportional gas counters to detect passing epithermal neutrons (Zreda et al., 2012; Schrön, Zacharias, et al., 2018; Köhli et al., 2018). Their count rates are typically measured in counts per hour (cph) or counts per minute (cpm).

2.1 From neutrons to water

The measured neutrons respond to all static and dynamic hydrogen pools in the footprint, such as water in soils (Scheiffele et al., 2020), vegetation (Jakobi et al., 2018), and snow (Schattan et al., 2019). They are corrected for the effect of variable air pressure, air humidity, and incoming cosmic rays (Zreda et al., 2012; Hawdon et al., 2014; Schrön et al., 2016) using direct measurements or data from weather services. The relationship between corrected neutrons, N, and the total water θ contained in the various pools has been described by Desilets, Zreda, and Ferré (2010) and adopted by most authors in the last decade. According to analysis from Köhli, Weimar, Schrön, and Schmidt (2021) it can be reformulated as:

$$\theta(N) \approx p_0 \, \frac{1 - N/N_{\max}}{p_1 - N/N_{\max}} \,, \tag{1}$$

where $N_{\max}$ is the maximum neutron flux under dry conditions which mainly depends on the individual detector sensitivity, but has also been suspected to reflect site-specific conditions (Zreda et al., 2012). Parameters $p_0 = -0.115$, $p_1 = 0.346$, and $N_{\max} = 1.075\,N_0$ can be derived from the parameters used so far in the Desilets equation (Desilets et al., 2010) which most of the previous research studies refer to. Here, $N_{\max}$ (or N_0) represents site- and detector-specific efficiency and is often used as a calibration parameter. In order to generate gravimetric and volumetric soil moisture products, we account for soil bulk density, soil lattice water, and organic material as described in Dong et al. (2014); McJannet et al. (2017); Schrön, Rosolem, et al. (2018) using the soil grids database (Hengl et al., 2017). Road-effect corrections are only applied for car-borne roving following Schrön, Rosolem, et al. (2018) and should be adapted to railways in future research. Those and other factors could introduce systematic uncertainty to a specific derived product as has been quantified by Baroni et al. (2018) and Jakobi et al. (2020). In addition, Fersch et al. (2018) suggested a method to reduce uncertainties from landscape heterogeneity passed by the moving detector. Nevertheless, all measurements have a lower limit of stochastic uncertainty in common due to the random nature of neutron detection.

2.2 Stochastic measurement uncertainty and spatial resolution

High count rates are essential to ensure a sufficiently high signal-to-noise ratio and reliable data products. Mobile measurements require a particularly high sensor efficiency to reduce the data accumulation period and the corresponding areal coverage (i.e., footprint length). This balance is a major challenge for large-scale CRNS applications that inextricably links measurement quality with spatial resolution.

Due to the non-linearity of Eq. 1, the propagated water content uncertainty, $\pm\sigma_\theta = \theta(N) - \theta(N \mp \sigma_N)$, is highly asymmetric. For simplicity, it can be estimated by a symmetrical approximation approach suggested by Jakobi et al. (2020):

$$\sigma_\theta \approx \sigma_N \frac{p_2\, N_0}{(N - p_3\, N_0)^4} \sqrt{(N - p_3\, N_0)^4 + 8\,\sigma_N^2 (N - p_3\, N_0)^2 + 15\,\sigma_N^4}\,, \tag{2}$$

where the count rate $N(\theta)$ follows from Eq. 1, $\sigma_N \sim \sqrt{N}$ is its Gaussian uncertainty, N_0 represents the detector-specific efficiency, and $p_2 = 0.0808$, $p_3 = 0.372$. The more neutrons N are collected per measurement, the lower are the signal-to-noise ratio σ_N/N and consequently the lower the uncertainty of the soil moisture product, σ_θ. N depends primarily on the water content, but it is ultimately constrained by detector type, aggregation window, and background radiation intensity. To express these dependencies, we introduce a new practical quantity, the so-called *base counts*:

$$N_{0,\text{base}} = N_0 \times a \times b, \tag{3}$$

where the aggregation factor a (in minutes) is the rolling filter window or record period over which neutron counts are aggregated (Schrön, Zacharias, et al., 2018), and $b \sim \exp(\beta\, P)$ is the barometric factor which accounts for the cosmic radiation dependency on air pressure P at various altitudes (see Hendrick & Edge, 1966; Desilets et al., 2006, and supplement material S1). The detector used in this study typically runs at $N_0 \approx 200\,\text{cpm}$ at sea level, which corresponds to base counts of 200–1200 for temporal resolutions of $a = 1$–6 minutes, respectively.

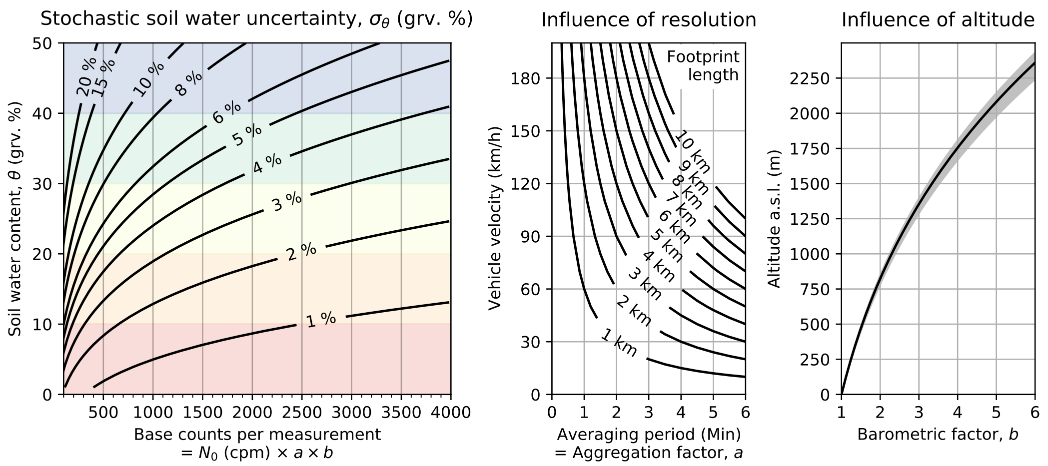

Figure 2. Stochastic measurement uncertainty σ_θ (in absolute gravimetric percent) based on actual soil moisture θ, the type of detector used, target spatiotemporal resolution, and typical topographic elevation. Base counts per measurement denotes the potential total number of counts collected during a given aggregation period at a certain altitude. For example, a detector with characteristic $N_0 = 500\,\text{cpm}$ at sea level could generate soil moisture products with 1–18 % uncertainty at 1 minute resolution. With a 3-minute moving average filter (factor $a = 3$) at 820 m altitude (factor $b = 2$), this would be equivalent to 3000 base counts and 0.5–6.1 % uncertainty. The temporal aggregation, however, also stretches out the footprint from 1 to 3 km at 60 km/h speed. Shaded area of the barometric line indicates the parameter range of $\beta = 135 \pm 5\,\text{hPa}$.

For increasing a, the footprint gets stretched out along the track and thereby increases the spatial scale of the measurement:

$$\text{footprintlength} \quad L = v \cdot a/60\,, \tag{4}$$

With the velocity v (in km/h) and aggregation window a (in minutes) this leads to footprint lengths of several kilometers. This already indicates an imminent tradeoff between the vehicle's travel speed and spatial resolution.

Figure 2 shows the uncertainty range of the derived soil water content (Eqs. 1 and 2) that can be obtained with different base counts $N_{0,\text{base}}$ (Eq. 3). Due to the non-linearity of Eq. 1, the method provides a range of uncertainties from dry to wet conditions. Higher base counts, e.g. determined by more efficient detectors, longer aggregation periods (middle panel), or higher topographic elevation (right panel), lead to a substantial decrease of σ_θ. In the case of regularly operated train routes, there is even a fourth option to reduce the uncertainty along a track by repeated measurements during the day. The number of repetitions would improve the measurement precision in a similar way as the aggregation factor a.

2.3 Sensitivity analysis of neutron detection in a train wagon

The hypothesis that neutron detectors can be used inside a train to measure water content in the surrounding area is not trivial, but has been supported by previous experiments using cars and by theoretical studies of neutron transport physics. In order to more specifically assess potential effects of train-like environments to the detection efficiency, we set up neutron transport simulations with the Monte-Carlo tool URANOS (Köhli et al., 2015, 2018). In the model we defined rails as 25x25 cm steel bars and a 3 or 9 m wide track bed as soil with 6 % water content in accordance to data from Iżvolt et al. (2016). Two types of wagons have been modelled, an "open" wagon consisting of a 10 cm thick steel plate at the bottom, and a "closed" wagon with additional ceiling (10 cm

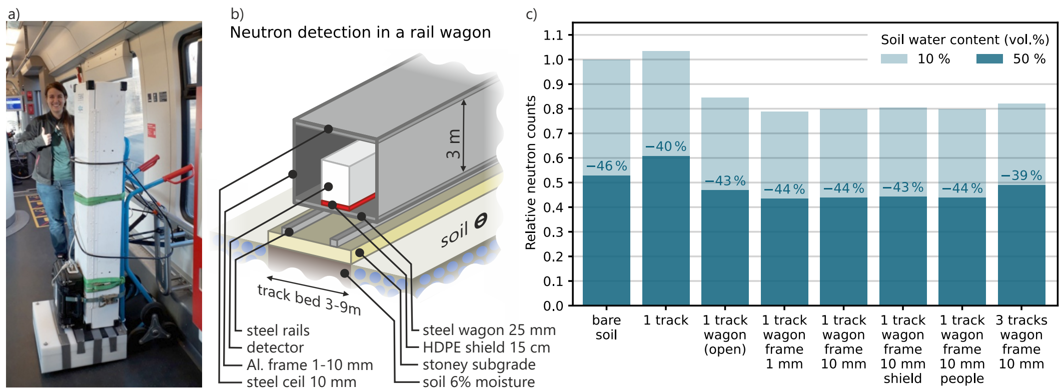

Figure 3. a) The CRNS Rail Rover system mounted on a dolly in a train. b) Simulation design of a rail track and wagon made of steel bottom, steel ceiling, and an aluminium frame. c) Simulation results show the dependency of the neutron count rate on dry and wet soil in various scenarios: 1 track (3 m), 3 parallel tracks (9 m), an open wagon without frames/ceiling, aluminium frames of different widths, 15 cm HDPE shielding below the detector (cmp. photograph), and the presence of people in adjacent wagons at 25 m distance from the (empty) detector wagon. A constant relative span between neutrons under dry and wet conditions (given in %) indicates constant measurement precision and general applicability of the $\theta(N)$ relationship independent of the housing.

steel of 1/10 density, i.e., effectively 1 cm thickness) and an aluminium frame at the sides of various widths. The whole train box exhibits a width of 3 m and contains a 1.5×0.5 m detector and an optional 15 cm thick polyethylene plate (HDPE) below. The latter is an experimental method aimed at reducing potential local effects (known as the *road-effect*, Schrön, Rosolem, et al., 2018). Humans in adjacent wagons (25 m distance from the detector) may depict an additional source of hydrogen in the sensor's footprint and have been modeled by 1.5×0.5 m objects of humid gas with 30 kg/m^2 water content.

The simulation results in Fig. 3 show the overall count rate for dry soil (light blue) relative to a bare soil scenario (first bar). They also emphasize the expected intensity drop for wet soil (dark blue), which is a measure for the sensitivity to soil moisture changes. The single track scenario (3 m width, second bar) increases the overall count rate, as expected from the known road effect, but simultaneously reduces the sensor sensitivity from 46 to 40 %. The steel bottom of the open wagon (bar 3) reduced the count rate by 18 %, but also restocks the sensitivity to 43 %. This bottom material thereby reduces the local effect of the track bed by half such that even the additional support of the much smaller HDPE shield becomes negligible, as indicated by the sixth bar. In the closed wagon, the steel ceiling also reduces the count rate by a few more percent, while the frame width does not seem to have significant influence on the signal (bars 4–5). Crowded adjacent wagons do not show substantial influence, but two additional rail tracks (total width of 9 m) again reduce the sensitivity to soil moisture.

It is important to note that measurement sensitivity, i.e. the neutron response to soil moisture between 10 and 50 % volumetric water content, remains almost unchanged throughout all scenarios. Wide track beds have the largest influence on the sensitivity, but this effect is already well understood and correction approaches for roads exist (Schrön, Rosolem, et al., 2018). The results indicate that the standard relationships to convert neutrons to soil moisture (Eq. 1) can be applied for CRNS monitoring using train wagons and probably need only very minor adaptions for specific vehicle configurations.

3 Experimental proof of concept

Experiments along various train tracks have been performed to verify the theoretical considerations with empirical evidence. The detector used in this study is similar to the one used by Schrön, Rosolem, et al. (2018) with an original record period of 10 seconds and a 15 cm polyethylene shield at the bottom. It has been fixed in a vertical mode on a dolly to ensure easy movement by a single person (see Fig. 3).

3.1 Detecting landscape features with a regional train

The first experiment challenges the hypothesis of whether or not a detector inside a train is capable of detecting environmental changes of water content outside a moving train wagon. The railway from Leipzig to Berlin passes several different natural and urban landscape features at an altitude of ~ 50 m a.s.l. and 30–140 km/h. On a ride in January 2019 their influence on the neutron response has been observed and shown exemplarily in Fig. 4. Nearby lakes, swamps, and forests substantially decreased the count rate (depending on their distance to the railway) due to their higher amount of water content. An intensity increase has been observed particularly in urban areas and near highly artificial structures, such as road network infrastructure, where stones, drainages, and dry and dense soil have been assembled. Underpass stations and underground tracks led to an extraordinary drop of the count rates, which almost ceased in deeper tunnels. This expected behaviour is just natural due to the limited penetration depth of atmospheric cosmic-ray neutrons. Residual neutron intensity can be explained by the natural background radiation of soils (Missimer et al., 2019) and by the large scattering length of neutrons in air following underground pathways (Köhli et al., 2015).

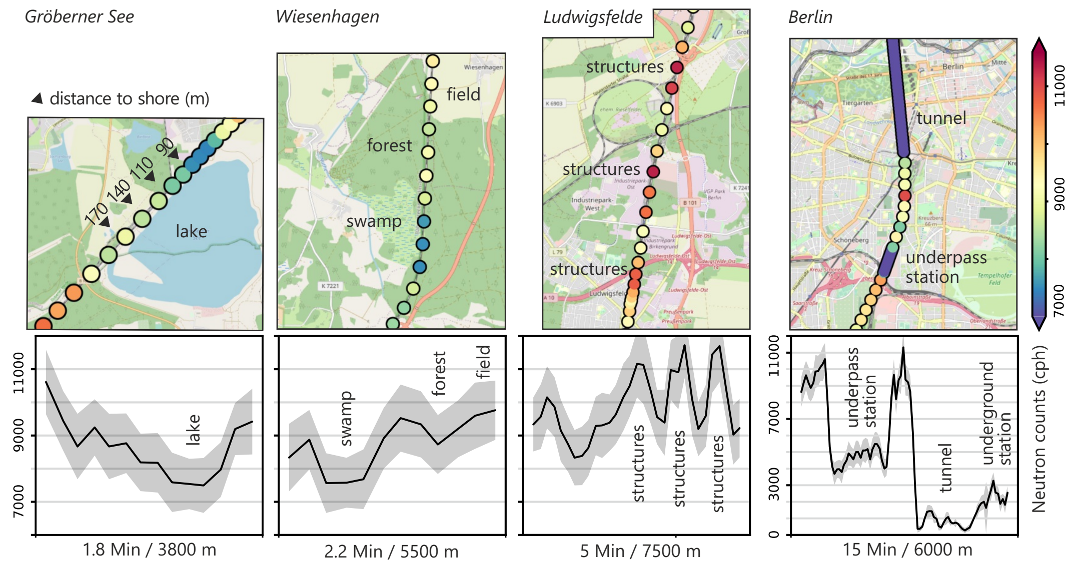

Figure 4. Exemplary sections from the train ride with a regional train from Leipzig to Berlin. Measurement points are visualized along the path at the end of each record period (10 sec). Neutron count rates drop on passing lake *Gröberner See* and on passing a swamp near *Wiesenhagen*. High count rates can be observed near extensive motorway or railway structures, large concrete areas or buildings. The cosmogenic neutron radiation drops substantially at a station underpassing a massive railway bridge, and it almost vanishes in the 14 m deep tunnel below the groundwater level in Berlin. Map background provided by OpenStreetMap.

3.2 Train-based regional soil moisture measurements and groundtruthing

Groundtruthing of CRNS measurements on rails with conventional point measurements is a difficult challenge due to the mismatch of scales. To make groundtruthing possible, we used car-borne CRNS roving, which has been extensively validated by various independent measurements already in previous studies (e.g. Schrön, Rosolem, et al., 2018). Between the German cities Dessau and Zerbst, the train route is often crossed by regular roads which in some parts also run in the close vicinity to the track. Measurements were conducted on the train several times a day at ~ 60 m a.s.l. and 60–120 km/h. Afterwards, the sensor was loaded into a car in horizontal mode and without bottom shield, and the railway route was followed on nearby roads. Occasionally, additional soil moisture measurements were taken using a hand-held TDR device at 0–10 cm depth along the track. The sparse data (not shown) ranged between 1 and 7 %, confirming the very dry conditions on that day as well as the overall performance of the mobile CRNS technique in this region.

Figure 5 presents the CRNS railway measurements (blue) and CRNS rover measurements within < 150 m distance around the railway. The neutron data has been filtered with a 1-minute moving average window and converted to soil moisture using $N_{\text{max}} = 223$ cpm. Car-borne rover processing and parameters were similar to Schrön, Rosolem, et al. (2018) with corrections for 5 m-wide concrete roads. The measurements on rails and on roads show a good agreement along the track despite the only partial spatial overlap, the different type of vehicles used, and potential influence of track beds and passenger fluctuations. The influence of those and other local environmental features to both methods might be substantial (Schrön et al., 2017; Schrön, Rosolem, et al., 2018; Fersch et al., 2018) and may pose some challenge for future signal processing.

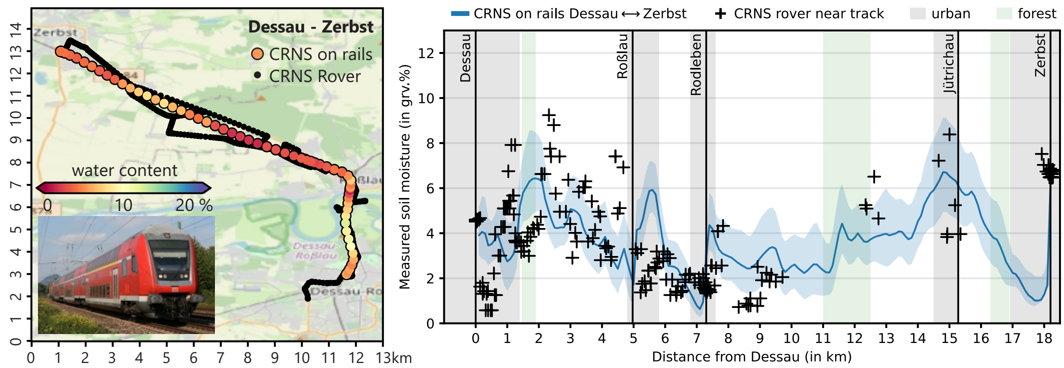

Figure 5. Validation experiment at the rail track between *Dessau* to *Zerbst* with a CRNS system in a local train (blue line and shaded stochastic error) and the same CRNS system in a car (CRNS rover) at accessible roads within $<$ 150 m near the railway (black cross) under particularly dry summer conditions (RMSE=1.9 %). The track passed a number of urban areas, nearby forests, and served two railway stations, *Roßlau* and *Rodleben*, which may have led to fluctuations of passengers. Map background provided by OpenStreetMap.

3.3 Train-based long-distance measurement of snow water equivalent

To examine the capabilities of mobile CRNS on trans-regional railways, we conducted a long-distance experiment in February 2019 using a regional train from Garmisch-Partenkirchen (pre-alpine, southern Germany) to Munich, and a high-speed train from Munich to Leipzig (lowland, central Germany). The train journey covered altitudes from 735 to 200 m a.s.l. and ran at 50–250 km/h. Data on air temperature and air humidity were taken from the German weather services. Incidental gaps in the GPS signal (due to the electrostatic shielding of train windows) were interpolated linearly.

Figure 6 presents the measured neutron counts versus the 5 km product of Snow Water Equivalent (SWE) based on space-borne microwave radiometry and weather station data (Pulliainen, 2006; Takala et al., 2011). Since the separation of snow and soil water from the signal is still an open research topic, we do not offer a final SWE product from CRNS at this stage of the analysis. The data, however, already show a clear correlation between SWE obtained from remote sensing and neutron counts on rails, up to the observed maximum of 80 mm SWE, which is in accordance with the theory and observations made with stationary CRNS sensors (Schattan et al., 2017, 2019; Bogena et al., 2020). Larger values of snow pack could be expected near Garmisch-Partenkirchen following the topographic trend, however, these space-borne products are not available in complex alpine terrain (grey shaded area in the figure). The variability of the neutron counts and SWE measurements can be attributed to the larger CRNS uncertainty under wet conditions as well as the high heterogeneity of snow pack which is represented differently by both methods (Schattan et al., 2017).

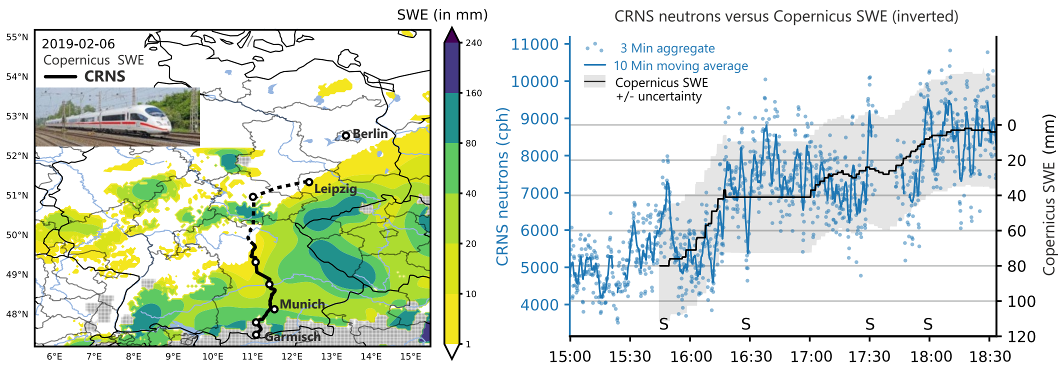

Figure 6. Left: Railway experiment on a long-distance train journey between *Garmisch-Partenkirchen* and *Leipzig* along a clear snow gradient (color scale). Note that mountainous regions cannot be resolved by this remote sensing product (hashed areas). Right: Measured neutrons (blue) show an inverse dependence on surrounding snow water equivalent (SWE) as indicated by the 5 km satellite product (black, inverted). Frequent variability indicates spatial heterogeneity along the railway track which is differently represented by the two methods. The letter "S" indicates railway stations.

4 Future challenges and potential for large-scale geophysics

This study demonstrates a proof of concept for trans-regional monitoring of soil water content and snow with cosmic-ray neutron sensors on rails. Theoretical considerations showed that the stochastic precision of derived soil moisture lies in the range of 0.5–3 % or 5–25 % for dry or wet soil, respectively. It largely depends on the detector efficiency, altitude, and averaging period. The latter also influences the spatial resolution, which could span several kilometers depending on vehicle velocity. Repeated transits along the same route would further contribute to higher measurement precision. Simulations revealed that the sensitivity to soil water changes remains almost unchanged for sensors in trains, suggesting that the same processing approaches are applicable as for the established method of car-borne CRNS roving. Several experiments in different trains provided clear evidence for significant neutron response to surrounding changes of water content and confirmed the theoretical considerations.

The footprint of mobile neutron measurements could cover up to half of a km^2 pixel. While currently there is a lack of alternative geophysical methods which could observe root-zone water content at comparable scales (Binley et al., 2015), further research is needed to resolve a potential spatial scale mismatch to remote-sensing or model resolutions. Future studies are also required to further test this method under variable conditions. Calibration and validation along the railway will remain a difficult challenge in the future but could be addressed by car-borne roving or mobile soil moisture sensor networks. Future research should particularly investigate ways to correct the signal for non-hydrological features, e.g. track beds, urban structures, or forest biomass. Artificial intelligence or the application of elementary orthogonal functions could be promising approaches to identify those constant spatial patterns (Finkenbiner et al., 2019). Dynamic train load, such as cargo or human passengers, may have little impact as long as the sensor system is located in a separate wagon.

The method indicates huge potential for large-scale mapping of soil water in the root zone and snow. Due to regular train traffic in public or cargo transport at national and international scales, CRNS on rails has the potential to become a highly distributed technique with minimal infrastructural investment. The method could be particularly useful on slow-moving trains in mountainous regions, where hydrological research is currently very limited by low coverage of observations, while models and satellite products still have issues with complex terrain and weather conditions. Due to the hectare-scale footprint and the potentially large spatial extent, CRNS on rails could make an important contribution to filling the critical gaps between in-situ data, hydrologic modeling, and remote sensing products. Smart combinations of CRNS on rails, remote sensing, models, and regionalization approaches could have the potential to support near-realtime drought monitors and other forecasting systems beyond the regional scale.

Acknowledgments

Data can be found in the supplementary material and will be uploaded to the *PANGAEA Data Publisher* upon acceptance of this manuscript. Satellite SWE products have been downloaded from the Copernicus data platform, `https://land.copernicus.eu/global/products/swe`. We acknowledge German Weather Service (DWD) for air humidity and temperature data and the NMDB database (`www.nmdb.eu`), founded under the European Union's FP7 program (contract 213007) for providing data for incoming radiation from the Jungfraujoch monitor (Physikalisches Institut, University of Bern). We thank Carmen Zengerle, Riad Khalaf-Saed, Claudia Schütze, Markus Köhli, Daniel Rasche, and Daniel Altdorff for fruitful discussions and support during the campaigns. Special thanks goes to the public transportation service "Deutsche Bahn AG" for their support during the regular operation. The work was funded by the DFG (German Research Foundation) via the project 357874777, research unit FOR 2694 *Cosmic Sense*, and has been made possible by the infrastructural funds of the Helmholtz Association, the Terrestrial Environmental Observatories (TERENO), and Modular Observation Solutions of Earth Systems (MOSES).

References

Andreasen, M., Jensen, K. H., Desilets, D., Franz, T. E., Zreda, M., Bogena, H. R., & Looms, M. C. (2017, 8). Status and Perspectives on the Cosmic-Ray Neutron Method for Soil Moisture Estimation and Other Environmental Science Applications. *Vadose Zone Journal*, *16*(8). doi: 10.2136/vzj2017.04.0086

Baroni, G., Scheiffele, L. M., Schrön, M., Ingwersen, J., & Oswald, S. E. (2018, SEP). Uncertainty, sensitivity and improvements in soil moisture estimation with cosmic-ray neutron sensing. *Journal of Hydrology*, *564*, 873–887. doi: 10.1016/j.jhydrol.2018.07.053

Binley, A., Hubbard, S. S., Huisman, J. A., Revil, A., Robinson, D. A., Singha, K., & Slater, L. D. (2015). The emergence of hydrogeophysics for improved understanding of subsurface processes over multiple scales. *Water resources research*, *51*(6), 3837–3866.

Bogena, H. R., Herbst, M., Huisman, J. A., Rosenbaum, U., Weuthen, A., & Vereecken, H. (2010, 11). Potential of wireless sensor networks for measuring soil water content variability. *Vadose Zone Journal*, *9*(4), 1002–1013. doi: 10.2136/vzj2009.0173

Bogena, H. R., Herrmann, F., Jakobi, J., Brogi, C., Ilias, A., Huisman, J. A., ... Pisinaras, V. (2020). Monitoring of snowpack dynamics with cosmic-ray neutron probes: A comparison of four conversion methods. *Frontiers in water*, *2*, 19. doi: 10.3389/frwa.2020.00019

Chan, S. K., Bindlish, R., O'Neill, P. E., Njoku, E., Jackson, T., Colliander, A., ... others (2016). Assessment of the smap passive soil moisture product. *IEEE Transactions on Geoscience and Remote Sensing*, *54*(8), 4994–5007.

Desilets, D., Zreda, M., & Ferré, T. P. A. (2010, 11). Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays. *Water Resources Research*, *46*. doi: 10.1029/2009WR008726

Desilets, D., Zreda, M., & Prabu, T. (2006). Extended scaling factors for in situ cosmogenic nuclides: new measurements at low latitude. *Earth and Planetary Science Letters*, *246*(3-4), 265–276.

Dong, J., Ochsner, T. E., Zreda, M., Cosh, M. H., & Zou, C. B. (2014, 04). Calibration and validation of the cosmos rover for surface soil moisture measurement. *Vadose Zone Journal*, *13*(4). doi: 10.2136/vzj2013.08.0148

Dorigo, W., Himmelbauer, I., Aberer, D., Schremmer, L., Petrakovic, I., Zappa, L., ... others (2021). The international soil moisture network: serving earth system science for over a decade. *Hydrology and Earth System Sciences Discussions*, 1–83. doi: 10.5194/hess-2021-2

Douville, H., & Chauvin, F. (2000). Relevance of soil moisture for seasonal climate predictions: A preliminary study. *Climate Dynamics*, *16*(10), 719–736.

Evans, J. G., Ward, H. C., Blake, J. R., Hewitt, E. J., Morrison, R., Fry, M., … Jenkins, A. (2016). Soil water content in southern england derived from a cosmic-ray soil moisture observing system – cosmos-uk. *Hydrological Processes*, *30*(26), 4987–4999. doi: 10.1002/hyp.10929

Fang, B., & Lakshmi, V. (2014). Soil moisture at watershed scale: Remote sensing techniques. *Journal of hydrology*, *516*, 258–272.

Fersch, B., Francke, T., Heistermann, M., Schrön, M., Döpper, V., Jakobi, J., … others (2020). A dense network of cosmic-ray neutron sensors for soil moisture observation in a pre-alpine headwater catchment in germany. *Earth System Science Data Discussions*, 1–35. doi: 10.5194/essd-12-2289-2020

Fersch, B., Jagdhuber, T., Schrön, M., Völksch, I., & Jäger, M. (2018). Synergies for Soil Moisture Retrieval Across Scales From Airborne Polarimetric SAR, Cosmic Ray Neutron Roving, and an In Situ Sensor Network. *Water Resources Research*, *54*(11), 9364–9383. doi: 10.1029/2018wr023337

Finkenbiner, C. E., Franz, T. E., Gibson, J., Heeren, D. M., & Luck, J. (2019). Integration of hydrogeophysical datasets and empirical orthogonal functions for improved irrigation water management. *Precision Agriculture*, *20*(1), 78–100.

Foucras, M., Zribi, M., Albergel, C., Baghdadi, N., Calvet, J.-C., & Pellarin, T. (2020). Estimating 500-m resolution soil moisture using sentinel-1 and optical data synergy. *Water*, *12*(3), 866.

Franz, T. E., Zreda, M., Ferré, T. P. A., & Rosolem, R. (2013). An assessment of the effect of horizontal soil moisture heterogeneity on the area-average measurement of cosmic-ray neutrons. *Water Resources Research*, *49*(10), 6450–6458. doi: 10.1002/wrcr.20530

Hawdon, A., McJannet, D., & Wallace, J. (2014). Calibration and correction procedures for cosmic-ray neutron soil moisture probes located across Australia. *Water Resources Research*, *50*(6), 5029–5043. doi: 10.1002/2013WR015138

Hendrick, L., & Edge, R. (1966). Cosmic-ray neutrons near the earth. *Physical Review*, *145*(4), 1023.

Hengl, T., de Jesus, J. M., Heuvelink, G. B. M., Gonzalez, M. R., Kilibarda, M., Blagotić, A., … others (2017). Soilgrids250m: Global gridded soil information based on machine learning. *PLoS one*, *12*(2).

Ižvolt, L., Dobeš, P., & lžbeta Pultznerová. (2016). Monitoring of moisture changes in the construction layers of the railway substructure body and its subgrade. *Procedia Engineering*, *161*, 1049 - 1056. doi: 10.1016/j.proeng.2016.08.847

Jakobi, J., Huisman, J. A., Schrön, M., Fiedler, J., Brogi, C., Vereecken, H., & Bogena, H. R. (2020). Error estimation for soil moisture measurements with cosmic ray neutron sensing and implications for rover surveys. *Frontiers in Water*, *2*, 10. doi: 10.3389/frwa.2020.00010

Jakobi, J., Huisman, J. A., Vereecken, H., Diekkrueger, B., & Bogena, H. R. (2018, 10). Cosmic Ray Neutron Sensing for Simultaneous Soil Water Content and Biomass Quantification in Drought Conditions. *Water Resources Research*, *54*(10), 7383–7402. doi: 10.1029/2018WR022692

Köhli, M., Schrön, M., & Schmidt, U. (2018). Response functions for detectors in cosmic ray neutron sensing. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *902*, 184–189. doi: 10.1016/j.nima.2018.06.052

Köhli, M., Schrön, M., Zreda, M., Schmidt, U., Dietrich, P., & Zacharias, S. (2015). Footprint characteristics revised for field-scale soil moisture monitoring with cosmic-ray neutrons. *Water Resources Research*, *51*(7), 5772–5790. doi: 10.1002/2015WR017169

Köhli, M., Weimar, J., Schrön, M., & Schmidt, U. (2021). Moisture and humidity dependence of the above-ground cosmic-ray neutron intensity. *Frontiers in*

Water, *2*, 66. doi: 10.3389/frwa.2020.544847
Lavoué, F., Coutant, O., Boué, P., Pinzon-Rincon, L., Brenguier, F., Brossier, R., … Bean, C. J. (2021). Understanding seismic waves generated by train traffic via modeling: Implications for seismic imaging and monitoring. *Seismological Society of America*, *92*(1), 287–300. doi: 10.1785/0220200133
Lawford, R. (2014). *The geoss water strategy: From observations to decisions.* Japan Aerospace Exploration Agency.
Lehning, M., Bartelt, P., Brown, B., Russi, T., Stöckli, U., & Zimmerli, M. (1999). Snowpack model calculations for avalanche warning based upon a new network of weather and snow stations. *Cold Regions Science and Technology*, *30*(1-3), 145–157.
Liang, M., & Yuan, X. (2021). Critical role of soil moisture memory in predicting 2012 central usa flash drought. *Frontiers in Earth Science*, *9*, 46.
Mattia, F., Balenzano, A., Satalino, G., Lovergine, F., Peng, J., Wegmuller, U., … others (2018). Sentinel-1 & sentinel-2 for soil moisture retrieval at field scale. In *Igarss 2018-2018 ieee international geoscience and remote sensing symposium* (pp. 6143–6146).
McJannet, D., Franz, T., Hawdon, A., Boadle, D., Baker, B., Almeida, A., … Desilets, D. (2014). Field testing of the universal calibration function for determination of soil moisture with cosmic-ray neutrons. *Water Resources Research*, *50*(6), 5235–5248. doi: 10.1002/2014WR015513
McJannet, D., Hawdon, A., Baker, B., Renzullo, L., & Searle, R. (2017). Multiscale soil moisture estimates using static and roving cosmic-ray soil moisture sensors. *Hydrology and Earth System Sciences*, *21*(12), 6049–6067. doi: 10.5194/hess-21-6049-2017
Missimer, T. M., Teaf, C., Maliva, R. G., Danley-Thomson, A., Covert, D., & Hegy, M. (2019). Natural radiation in the rocks, soils, and groundwater of southern florida with a discussion on potential health impacts. *International journal of environmental research and public health*, *16*(10), 1793.
Ochsner, T. E., Cosh, M. H., Cuenca, R. H., Dorigo, W. A., Draper, C. S., Hagimoto, Y., … Zreda, M. (2013). State of the art in large-scale soil moisture monitoring. *Soil Science Society of America Journal*, *77*(6), 1888-1919. doi: 10.2136/sssaj2013.03.0093
Pan, F., & Peters-Lidard, C. D. (2008). On the relationship between mean and variance of soil moisture fields 1. *JAWRA Journal of the American Water Resources Association*, *44*(1), 235–242.
Pulliainen, J. (2006). Mapping of snow water equivalent and snow depth in boreal and sub-arctic zones by assimilating space-borne microwave radiometer data and ground-based observations. *Remote Sensing of Environment*, *101*(2), 257-269. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0034425706000241` doi: doi.org/10.1016/j.rse.2006.01.002
Romano, N. (2014). Soil moisture at local scale: Measurements and simulations. *Journal of Hydrology*, *516*, 6–20.
Schattan, P., Baroni, G., Oswald, S. E., Schoeber, J., Fey, C., Kormann, C., … Achleitner, S. (2017, 5). Continuous monitoring of snowpack dynamics in alpine terrain by aboveground neutron sensing. *Water Resources Research*, *53*(5), 3615–3634. doi: 10.1002/2016WR020234
Schattan, P., Köhli, M., Schrön, M., Baroni, G., & Oswald, S. E. (2019). Sensing area-average snow water equivalent with cosmic-ray neutrons: The influence of fractional snow cover. *Water Resources Research*, *55*(12), 10796–10812. doi: 10.1029/2019WR025647
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 Journal*, *19*(1), e20083. doi: doi.org/10.1002/vzj2.20083

Schelle, H., Durner, W., Schlüter, S., Vogel, H.-J., & Vanderborght, J. (2013). Virtual soils: Moisture measurements and their interpretation by inverse modeling. *Vadose Zone Journal*, *12*(3), 1–12.

Schrön, M., Köhli, M., Scheiffele, L., Iwema, J., Bogena, H. R., Lv, L., ... Zacharias, S. (2017, 10). Improving calibration and validation of cosmic-ray neutron sensors in the light of spatial sensitivity. *Hydrology and Earth System Sciences*, *21*(10), 5009–5030. doi: 10.5194/hess-21-5009-2017

Schrön, M., Rosolem, R., Köhli, M., Piussi, L., Schröter, I., Iwema, J., ... Zacharias, S. (2018, SEP). Cosmic-ray Neutron Rover Surveys of Field Soil Moisture and the Influence of Roads. *Water Resources Research*, *54*(9), 6441-6459. doi: 10.1029/2017WR021719

Schrön, M., Zacharias, S., Köhli, M., Weimar, J., & Dietrich, P. (2016). Monitoring environmental water with ground albedo neutrons from cosmic rays. In *The 34*$^{\text{th}}$ *international cosmic ray conference* (Vol. 236, p. 231). doi: 10.22323/1.236.0231

Schrön, M., Zacharias, S., Womack, G., Köhli, M., Desilets, D., Oswald, S. E., ... Dietrich, P. (2018). Intercomparison of cosmic-ray neutron sensors and water balance monitoring in an urban environment. *Geoscientific Instrumentation, Methods and Data Systems*, *7*(1), 83–99. doi: 10.5194/gi-7-83-2018

Takala, M., Luojus, K., Pulliainen, J., Derksen, C., Lemmetyinen, J., Kärnä, J.-P., ... Bojkov, B. (2011). Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements. *Remote Sensing of Environment*, *115*(12), 3517-3529. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0034425711003166` doi: doi.org/10.1016/j.rse.2011.08.014

Vather, T., Everson, C., & Franz, T. E. (2019). Calibration and validation of the cosmic ray neutron rover for soil water mapping within two south african land classes. *Hydrology*, *6*(3), 65. doi: 10.3390/hydrology6030065

Vogel, M. M., Zscheischler, J., & Seneviratne, S. I. (2018). Varying soil moisture–atmosphere feedbacks explain divergent temperature extremes and precipitation projections in central europe. *Earth System Dynamics*, *9*(3), 1107–1125. doi: 10.5194/esd-9-1107-2018

Zreda, M., Shuttleworth, W. J., Zeng, X., Zweck, C., Desilets, D., Franz, T. E., & Rosolem, R. (2012). COSMOS: the COsmic-ray Soil Moisture Observing System. *Hydrology and Earth System Sciences*, *16*(11), 4079-4099. doi: 10.5194/hess-16-4079-2012