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# *Comparison of cosmic-ray neutron sensing and gamma-ray spectrometry for non-invasive soil moisture estimation over a large cropped field*


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***Abstract*—Soil moisture is a key variable for supporting agriculture and forest management. This variable, however, shows strong variability in space and time and its correct quantification is still difficult in many practical applications. In the present study we compare two innovative non-invasive sensors developed for the estimation of soil moisture over large area. The first one is a new sensor based on cosmic-ray neutron sensing approach. The second one is a new gamma-ray spectrometer specifically designed for this type of application. Data have been collected at a large, cropped field at Ceregnano, Italy in 2021. The results show that both sensors well capture the local hydrological conditions, and they can be considered reliable methods for soil moisture estimations. In both sensors, however, the signal shows to also be sensitive even if to a different degree to water in the biomass, highlighting the need of corrections when fast plant growth is expected.**



***Keywords— neutrons, gamma ray, soil moisture, biomass, cropped field***


## I. INTRODUCTION

Soil moisture is a key variable for understanding the hydrological processes and for supporting the sustainable management of agricultural and forest environments [1].

Several methods to estimate soil moisture have been developed ranging from point scale sensors to remote sensing products [2], [3]. On the one hand, point-scale sensors are invasive techniques which consist in inserting a probe at a specific depth into the soil. In this case, the representativity of the measurement refers to few centimeters around the probe. Being a local measurement, the use of these methods can introduce large uncertainties due to the high spatial heterogeneity of soils, plants and water management conditions (irrigation and drainage). On the other hand, remote sensing is a non-invasive technique that monitor land surface properties that can be inverted for soil moisture estimation. Nowadays, remote sensing products can reach spatial and temporal resolution of ~ 1 kilometer and few days, respectively. For these reasons they can provide relevant information for many practical applications. However, vegetation and surface roughness strongly affect microwave SM observations. Moreover, its applicability at locations characterized by small fields and in real time is still limited [4].

To overcome these difficulties, more recently new non-invasive and passive techniques proximal to the soil surface have been developed and tested [5]. Among others, Cosmic Ray Neutron Sensing (CRNS) [6] and Gamma Ray Spectrometry (GRS) [7] have showed promising results in many conditions and they are now taking place for different applications [8]–[10].

Briefly, these techniques rely on detecting particles proximal to the surface such as thermalized neutrons and gamma rays which interacts mostly with hydrogen, present in nature as soil moisture and, in minor part, as water in the biomass of vegetated areas such as agricultural and forest environment. The inverse correlation between neutrons or gamma rays and hydrogen allows to have a soil water content estimation with a probe installed above ground. For further details we refer to specific literature, e.g., [11], [12].

In this study, we present a comparison of data collected by CRNS and GRS sensors at a soybean cropped field located at Ceregnano, north of Italy during the crop growing season 2021. Sensors are non-invasive, passive, proximal to the ground and especially designed for stationary recording of soil water content over a large area. CRNS and GRS raw and processed signals are firstly presented. The field campaigns conducted to collect soil samples for the calibration of the sensors and for quantifying the biomass water equivalent (BWE) are then described. Soil moisture estimation are then compared along with precipitation, irrigation and NDVI detected by remote sensing during the growing season. The difference between the two soil moisture estimations is further discussed.

## II. CASE STUDY

### A. Test site and detectors

The experimental site is located at Ceregnano (Rovigo, Italy), in a flat agricultural area of around 30 ha. The proximal ground sensors are installed on a pole at 1.90 m height, in the middle of the field. The site is characterized by sandy loam alluvial deposits and homogeneous soybean cultivation. Irrigation is managed with a variable rate irrigation rover designed for precision agriculture equipped with multiple sprinkler nozzles. The machine, 10 m high and 200 m large, moves over the field with constant speed and irrigating with a variable amount of water.

Fig. 1. Sensors installed at Ceregnano (Italy). The gSMS by Medusa on the left and CRNS by Finapp on the right.

On the left side of Fig. 1 , the gamma-ray soil moisture sensor gSMS by Medusa (https://medusa-online.com/ ) is shown. Based on the current sensor installation (height of installation), the detected signal can be considered representative of an area of around 1 ha in the horizontal plane and about 20-30 cm into the soil.

The instrument is specially designed for static measurements of natural occurring gamma emission during the radioactive decay of Potassium $^{40}K$ , Uranium $^{238}U$ , and Thorium $^{232}Th$ radionuclides. Specifically, the instrument is equipped with a 100 ml CsI crystal and connected to a multi-channel analyzed (MCA). A spectral analysis of total gamma signal is performed within the sensor to detect the counts of each different energy radionuclide range.

Potassium and Thorium isotopes are mostly present in the soil. Their gamma ray emission is attenuated by the presence of water in the ground and by vegetation growth. For this reason, these signals can be used to estimate soil moisture [10].

In contrast uranium radionuclides are mostly present in the atmosphere. Droplets arriving at the land surface gets rich in this element, increasing the count recorded by the sensor. For this reason, this signal is shown to be a good estimation to distinguish if an increase of soil moisture detected corresponds to an irrigation or a precipitation event [10], [13].

On the right side of Fig. 1, two CRNS-Finapp sensors (https://www.finapptech.com/) are shown. CRNS sensor have a bigger footprint in comparison to GRS probes of around 5 ha and depth down to 40-50 cm into the soil. One CRNS-Finapp sensor (below) is the standard neutron detector sensible to the epithermal energy range. This detects low-energy neutrons scattered and slowed by hydrogen present in the soil as soil moisture. On top of this, a neutron detector shielded with a Gadolinium layer is installed to remove the thermal neutrons that are still detected with the standard configuration. In the present article, only data from the first sensor are discussed and compared.

For each sensor, the energy supply is guaranteed individually by a solar panel charging a backup battery allowing for long-term monitoring. Weather data are acquired by a standard weather station operated by the environmental agency.

### B. Raw signals

We present in Fig. 2 data collected at Ceregnano site during four months of observations, from end of May to the end of September 2021, along with precipitation and irrigations. All the signals have been aggregated to hourly data smoothed with a running average of six hours. Neutrons have been corrected for atmospheric pressure and incoming variability based on current literature [14]–[16].

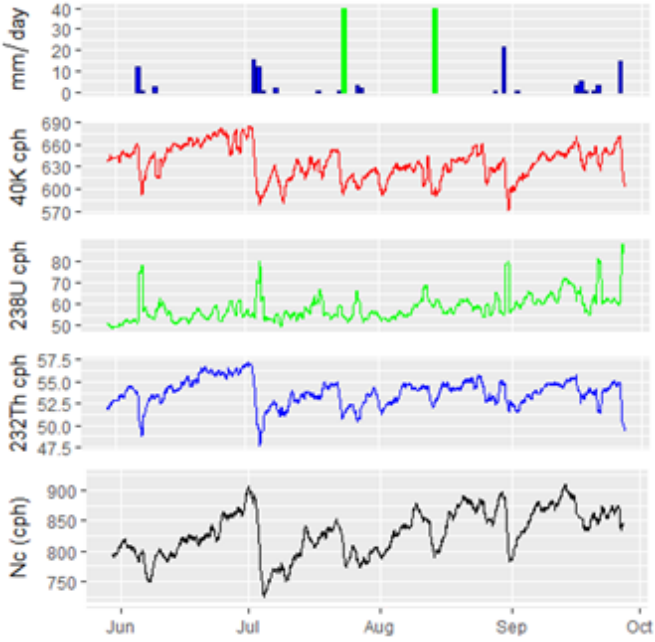


Fig. 2. From top to bottom, precipitation in blue and irrigation events in green; potassium, uranium and thorium radionuclides signals recorded by gSMS-Medusa; neutrons corrected for incoming and pressure variability measured by CRNS-Finapp.

The results show good agreement between all the signals. $^{40}K$ , $^{232}Th$ and neutrons counts decrease when a precipitation or irrigation event occurs due to the inverse correlation with soil moisture. During the drying periods between precipitations, counts tends to increase as the soil dries up and the water layer stops attenuating the emission of the soil. For $^{238}U$ radionuclide signal, peaks are in correspondence to precipitations highlighting an increase of concentration detected at near-ground level.

## III. Field campaigns and analyses for soil and biomass

Soil and biomass samples have been collected to convert neutrons and potassium radionuclide counts into soil moisture and for the assessment.

For the soil samples, two specific sampling designs (Fig. *3*) have been defined to address the footprint sensitivity of each instrument. Specifically, a set of 18 sample points are defined to quantify the average soil moisture content in the footprint area related to each single sensor. Soil samples were taken at every 60° angle and at distances of 120 - 35 - 3 m from the neutron sensor and 9 - 3 - 1 m for the gamma-ray sensor. At each location, soil samples have been collected at four mean depths of 5 - 15 - 25 - 35 cm from the soil surface.

A total of 84 undisturbed soil with known volume have been extracted. Please note that that the samples at radius 3 m are used as data valid for both sensors. Gravimetric soil moisture (g $g^{-1}$) and bulk density (g $m^{-3}$) are calculated for each sample by weight after drying in the oven at 105 ° Celsius for 24 hours.

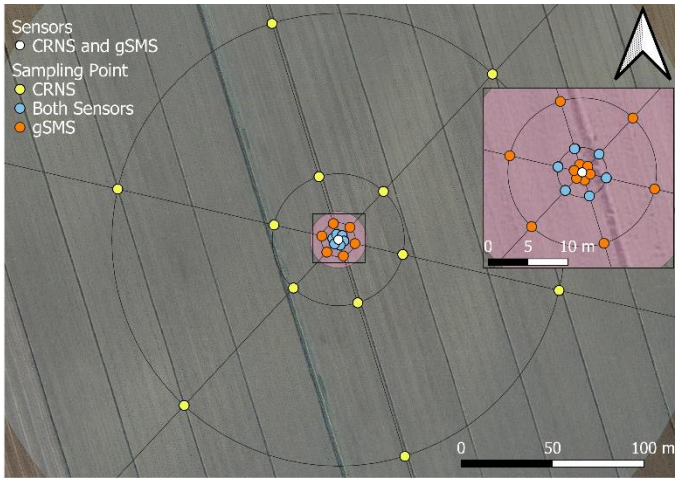


Fig. 3. Soil sampling design for CRNS (large footprint of around 120 m radius) and gSMS (smaller footprint of around 25 m radius).

Two soil campaigns have been conducted following this sampling design. The soil samples collected during the first campaign on 31st of May 2021 is used for the calibration of the sensors. The soil samples collected during the second campaign on 15th of July 2021 is used for comparison. Specifically, the arithmetic average value of the soil moisture in the footprint area of each sensor is used to calibrate the sensors and invert epithermal corrected neutron counts $N_c$ and potassium $^{40}K$ counts into soil moisture based on the following equations [13], [17]:

$$\theta_v(N_c) = \left(\frac{0.0808}{\frac{N_c}{N_0} - 0.372} - 0.115 - \theta_{offset}\right) \cdot \frac{\rho_{bd}}{\rho_w} \qquad (1)$$

$$\theta_v(\gamma) = \left(\frac{C_K^{Cal}}{C_K(t)} \left[\, 0.903 \, + \, w_g^{Cal} \,\right] - \, 0.903\right) \cdot \frac{\rho_{bd}}{\rho_w} \qquad (2)$$

where $\rho_{bd}$ and $\rho_w$ are respectively the soil bulk density and water density ($kg \cdot m^{-3}$), $\theta_{offset}$ is the contribution of static hydrogen pools (e.g., lattice water, soil organic carbon), $\theta_v(N_c)$ and $\theta_v(\gamma)$ are the soil moisture average during the day of calibration, $N_0$ and $C_K^{Cal}$ are the calibration parameters. $\theta_{offset}$ was quantified by means of loss-of-ignition method on a composite of the soil samples collected during the first campaign (see $\theta_{offset}$ in eq.1). For additional details see [18], [19]. The value of this additional hydrogen pool is considered representative for the entire growing season as temporal changes are not expected during this short period. Please also note that in the present contribution the arithmetic average of all the samples is used in (1) and in (2). The use of weighting functions has been suggested in literature for the processing of the soil data [7], [11] and they will be considered in future studies.

The detected signals are also affected by vegetation as an extra hydrogen pool that increases during the season. This factor can affect $^{40}K$ and neutrons lowering the counts in time and quantifying a water content which is a contribution both from vegetation and soil. For this reason, further activities have also been conducted to quantify and monitor the biomass during the season.

As a first approach, the vegetation growth of the homogenous soybean cropped field is monitored through the determination of NDVI by the analysis of multiple remote sensing Sentinel2 products. This allows to keep track of the trend of plant growth during the season. NDVI parameter is quantified over the red portion of the field in Fig. 4.

In addition, one field campaign has been conducted to collect vegetation samples on the 1st of October, few days before harvesting. In this case, six locations have been defined as reported in Fig. 4. At each location, plants over a meter square area have been counted, cut, and weighted in site and after oven-dry in the lab for 24h at 70° Celsius. Biomass water equivalent (BWE) was then quantified following [9].

Fig. 4. Vegetation sampling pattern for biomass water equivalent determination and area of interest for NDVI estimation based on Sentinel 2.

## IV. Results

Results of soil moisture and biomass water equivalent (BWE) collected during the field campaigns are reported in Tab. 1. Based on that, neutrons and potassium counts are converted in volumetric soil moisture content ($m^3$ $m^{-3}$) over the entire season by applying (1) and (2) for CRNS and GRS, respectively. The results are shown in Fig. 5.

TABLE I. CRNS SAMPLING DESIGN REFERS TO THE SOIL SAMPLES COLLECTED AT THE LOCATIONS IN THE LARGE FOOTPRINT OF FIG.3. THE GRS SAMPLING DESIGN REFERS TO THE SOIL COLLECTED AT THE LOCATIONS IN THE SMALL FOOTPRINT OF FIG.3.

| Variable | Technique | |
|---|---|---|
| | ***Based on CRNS sampling design*** | ***Based on GRS sampling design*** |
| Avg. Soil Moisture 31 May [g $g^{-1}$] | $0.179 \pm \mathbf{0.04}$ | $0.16 \pm \mathbf{0.04}$ |
| Avg. Soil Moisture 15 July [g $g^{-1}$] | $0.128 \pm \mathbf{0.03}$ | *null* |
| Counts per hour 31 May [cph] | 810 (Nc) | *650 (K40)* |
| SoilOrgnaicCarbon [g $g^{-1}$] | 0.036 | |
| LatticeWater [g $g^{-1}$] | 0.113 | |
| Bulk Density [g $cm^3$] | 1.363 | |
| Biomass Water Equivalent [mm] | 2.55 | |

The results show how both CRNS-based (black line in Fig. 5) and GRS-based (orange line in Fig. 5) soil moisture well reproduce the hydrological dynamic during the growing season. Fast increases are detected during precipitation and irrigation events and slow dry down is caused by evapotranspiration during input-free periods. The independent volumetric soil moisture values obtained during the sampling campaign on 15th of July 2021 (red point) indicates, however, an overestimation of both signal that can be already attributed to the biomass effect, as represented by the NDVI signal.

Noteworthy, the soil moisture estimated by the two sensors are, however, well in agreement but only during the first months. Differences increase during the growing season. Results suggest that GRS technique is more affected by the vegetation contribution lowering potassium counts rather than neutron counts.

We further assess this difference with the hypothesis that this contribution is due to biomass water equivalent (BWE) based on the following equation as suggested by [20],

$$BWE = (\theta_v(N_c) - \theta_v(\gamma)) * z^* \qquad (3)$$

where $\theta_v(N_c)$ and $\theta_v(\gamma)$ are the soil moisture over time for CRNS and GRS, respectively, and $z^*$ is the mean penetration depth of about 0.15 m calculated based on [21].

The results are shown in the bottom last panel of Fig. 5 (black line) together with the amount of BWE quantified during the vegetation field campaign on the 1st of October 2022 (dark green dot). The results show how BWE estimated based on (3) generally follow the seasonal trends of the crop growth. The estimation, however, does not reach the measured field value of BWE. This difference can be explained considering that both signals are affected to the vegetation growth but to a different degree.

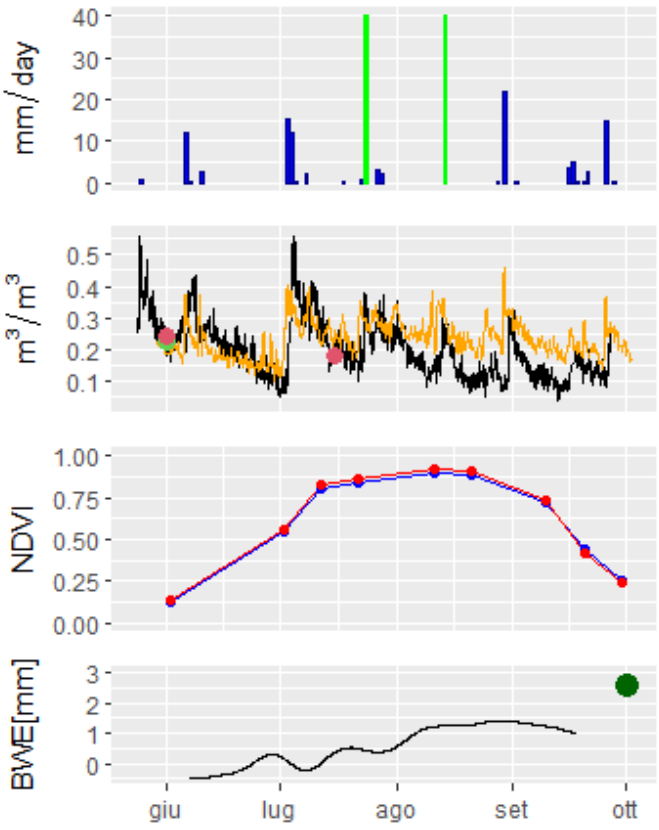


Fig. 5. From top to bottom, precipitation and irrigation data; comparison between CRNS (black line) and GRS (orange line) soil moisture signals along with volumetric soil moisture values resulted from the calibration and validation campaign; NDVI satellite derived signal; derived BWE signal as difference between soil moisture signals recorded by the sensors following (3) along with quantified BWE during the survey of the 1st of October.

## V. CONCLUSIONS

This study presents and compare data collected by two non-invasive soil moisture sensors at a large, cropped field in Italy during the season 2021. The results show that both cosmic-ray neutron sensing (CRNS) and gamma-ray spectrometry (GRS) sensors well capture the soil moisture dynamic at the site. Both signals are, however, affected but with different degrees by the fast biomass growth. For this reason, biomass correction should be considered when fast plant growth is expected. Despite some corrections have been proposed in literature, they are based on independent biomass measurements that should be conducted during the season. For this reason, further studies should focus on developing an easy-to-use approach that requires less invasive and time-consuming plant measurements.

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## REFERENCE

[1] S. I. Seneviratne *et al.*, “Investigating soil moisture–climate interactions in a changing climate: A review,” *Earth-Science Reviews*, vol. 99, no. 3–4, pp. 125–161, May 2010, doi: 10.1016/j.earscirev.2010.02.004.

[2] D. A. Robinson *et al.*, “Advancing process-based watershed hydrological research using near-surface geophysics: a vision for, and review of, electrical and magnetic geophysical methods,” *Hydrological Processes*, vol. 22, no. 18, pp. 3604–3635, Aug. 2008, doi: 10.1002/hyp.6963.

[3] T. E. Ochsner *et al.*, “State of the Art in Large-Scale Soil Moisture Monitoring,” *Soil Science Society of America Journal*, vol. 77, no. 6, p. 1888, 2013, doi: 10.2136/sssaj2013.03.0093.

[4] L. Brocca, L. Ciabatta, C. Massari, S. Camici, and A. Tarpanelli, “Soil Moisture for Hydrological Applications: Open Questions and New Opportunities,” *Water*, vol. 9, no. 2, Art. no. 2, Feb. 2017, doi: 10.3390/w9020140.

[5] H. R. Bogena *et al.*, “Emerging methods for noninvasive sensing of soil moisture dynamics from field to catchment scale: a review,” *Wiley Interdisciplinary Reviews: Water*, vol. 2, no. 6, pp. 635–647, Nov. 2015, doi: 10.1002/wat2.1097.

[6] M. Zreda, D. Desilets, T. P. A. Ferré, and R. L. Scott, “Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons,” *Geophysical Research Letters*, vol. 35, no. 21, Nov. 2008, doi: 10.1029/2008GL035655.

[7] M. Baldoncini *et al.*, “Investigating the potentialities of Monte Carlo simulation for assessing soil water content via proximal gamma-ray spectroscopy,” *Journal of Environmental Radioactivity*, vol. 192, pp. 105–116, Dec. 2018, doi: 10.1016/j.jenvrad.2018.06.001.

[8] L. M. Scheiffele, G. Baroni, T. E. Franz, J. Jakobi, and S. E. Oswald, “A profile shape correction to reduce the vertical sensitivity of cosmic-ray neutron sensing of soil moisture,” *Vadose Zone Journal*, vol. 19, no. 1, p. e20083, 2020, doi: 10.1002/vzj2.20083.

[9] T. E. Franz, T. Wang, W. Avery, C. Finkenbiner, and L. Brocca, “Combined analysis of soil moisture measurements from roving and fixed cosmic ray neutron probes for multiscale real-time monitoring,” *Geophysical Research Letters*, vol. 42, no. 9, pp. 3389–3396, 2015, doi: 10.1002/2015GL063963.

[10] V. Strati *et al.*, “Modelling Soil Water Content in a Tomato Field: Proximal Gamma Ray Spectroscopy and Soil–Crop System Models,” *Agriculture*, vol. 8, no. 4, p. 60, Apr. 2018, doi: 10.3390/agriculture8040060.

[11] M. Schrön *et al.*, “Improving calibration and validation of cosmic-ray neutron sensors in the light of spatial sensitivity,” *Hydrol. Earth Syst. Sci.*, vol. 21, no. 10, pp. 5009–5030, Oct. 2017, doi: 10.5194/hess-21-5009-2017.

[12] M. Baldoncini *et al.*, “Biomass water content effect on soil moisture assessment via proximal gamma-ray spectroscopy,” *Geoderma*, vol. 335, pp. 69–77, Feb. 2019, doi: 10.1016/j.geoderma.2018.08.012.

[13] A. Serafini *et al.*, “Proximal Gamma-Ray Spectroscopy: An Effective Tool to Discern Rain from Irrigation,” *Remote Sensing*, vol. 13, no. 20, p. 4103, Oct. 2021, doi: 10.3390/rs13204103.

[14] M. Zreda *et al.*, “COSMOS: the COsmic-ray Soil Moisture Observing System,” *Hydrology and Earth System Sciences*, vol. 16, no. 11, pp. 4079–4099, Nov. 2012, doi: 10.5194/hess-16-4079-2012.

[15] G. Baroni, *Spreadsheet for soil samples and CRNS data processing*. Zenodo, 2022. doi: 10.5281/zenodo.6782652.

[16] D. Power, M. A. Rico-Ramirez, S. Desilets, D. Desilets, and R. Rosolem, “Cosmic-Ray neutron Sensor PYthon tool (crspy 1.2.1): an open-source tool for the processing of cosmic-ray neutron and soil moisture data,” *Geoscientific Model Development*, vol. 14, no. 12, pp. 7287–7307, Nov. 2021, doi: 10.5194/gmd-14-7287-2021.

[17] D. Desilets, M. Zreda, and T. P. A. Ferré, “Nature’s neutron probe: Land surface hydrology at an elusive scale with cosmic rays,” *Water Resources Research*, vol. 46, no. 11, Nov. 2010, doi: 10.1029/2009WR008726.

[18] L. R. Barbosa *et al.*, “Dynamic groundwater recharge simulations based on cosmic-ray neutron sensing in a tropical wet experimental basin,” *Vadose Zone Journal*, vol. 20, no. 4, p. e20145, 2021, doi: 10.1002/vzj2.20145.

[19] J. L. Jensen, B. T. Christensen, P. Schjønning, C. W. Watts, and L. J. Munkholm, “Converting loss-on-ignition to organic carbon content in arable topsoil: pitfalls and proposed procedure,” *European Journal of Soil Science*, vol. 69, no. 4, pp. 604–612, Jul. 2018, doi: 10.1111/ejss.12558.

[20] G. Baroni and S. E. Oswald, “A scaling approach for the assessment of biomass changes and rainfall interception using cosmic-ray neutron sensing,” *Journal of Hydrology*, vol. 525, pp. 264–276, Jun. 2015, doi: 10.1016/j.jhydrol.2015.03.053.

[21] T. E. Franz *et al.*, “Measurement depth of the cosmic ray soil moisture probe affected by hydrogen from various sources,” *Water Resources Research*, vol. 48, no. 8, Aug. 2012, doi: 10.1029/2012WR011871.