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Article

A Novel Cosmic-Ray Neutron Sensor for Soil Moisture Estimation over Large Areas

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Abstract: A correct soil moisture estimation is a fundamental prerequisite for many applications: agriculture, meteorological forecast, flood and drought prediction, and, in general, water accounting and management. Traditional methods typically provide point-like measurements, but suffer from soil heterogeneity, which can produce significant misinterpretation of the hydrological scenarios. In the last decade, cosmic-ray neutron sensing (CRNS) has emerged as a promising approach for the detection of soil moisture content. CRNS can average soil moisture over a large volume (up to tens of hectares) of terrain with only one probe, thus overcoming limitations arising from the heterogeneity of the soil. The present paper introduces the development of a new CRNS instrument designed for agricultural applications and based on an innovative neutron detector. The new instrument was applied and tested in two experimental fields located in Potsdam (DE, Germany) and Lagosanto (IT, Italy). The results highlight how the new detector could be a valid alternative and robust solution for the application of the CRNS technique for soil moisture measurements in agriculture.

Keywords: CRNS; neutron; cosmic-ray; soil moisture; water; precision farming

1. Introduction

Water scarcity and drought problems in several parts of the world highlight the necessity for new solutions for better management of water resources. The Food and Agriculture Organization of the United Nations (FAO) calculates that 70% of employed water resources are dedicated to agriculture on the global scale [1]. Sustaining agricultural productivity requires an efficient management of agricultural water resources that involves a clear understanding of the temporal dynamics and spatial variability of soil moisture. Such dynamics are essential to optimize irrigation, preserve water for drought periods, and to optimize other production inputs, such as fertilizer application and water pumping power. The prerequisite is reliable soil moisture data, measured over large-scales and in real-time.

Due to this crucial role, many devices have been developed to measure soil moisture at different spatial and temporal scales [2–4]. Available technologies range from point-scale invasive approaches, like time domain reflectometry (TDR) probes [5], to satellite remote sensing approaches [6]. The former technology can achieve accurate measurements (RMSE, root-mean-square error <2%) at high temporal resolution (minutes) and at different soil depths [5]. However, difficulties arise for the coverage of large areas (e.g., >500 m^2), since soil heterogeneity can produce significant misinterpretation of hydrological conditions [4,7]. To monitor a large area, several point-scale probes must be installed, but this might generate technical problems (such as the definition of statistically relevant positions, electrical power supply, data transmission) and high costs, due to multiple instruments and to low accessibility of specific locations (especially in the case of extensive crops) [8–10]. Furthermore, their set-up in agricultural fields is limited by tillage and other land management operations and farming practices. In addition, the detectors are invasive (buried in the soil) and they require high maintenance. For these reasons, they are not suitable for covering heterogeneous and inaccessible sites (mountain sides and cropped fields) and they are expensive for long-term monitoring observatories.

A completely different alternative is represented by remote sensing approaches typically based on microwaves (1 mm–1 m). Compared to point-scale methods, satellite remote sensing provides soil moisture observations at a large scale (>km^2) and covers global areas, so it is more suitable for hydrological applications [11]. However, the signal is sensitive only to the very first centimeters of soil interface [12] and the temporal resolution (e.g., weekly measurements) is not always suitable for many applications. Large-scale satellite remote sensing methods have other limitations [13], including limited capability to penetrate vegetation, inability to measure soil ice, and sensitivity to surface roughness [14]. For these reasons, despite the progress over the last decades, accuracy of remote sensing estimation is still too high for several applications (e.g., RMSE >4%) [15] and many studies are focusing on possible improvements [6].

In the last decade, to overcome the aforementioned operational challenges, a proximal geophysical method has been developed in order to fill the gap between point-scale and remote sensing approaches: cosmic-ray neutron sensing (CRNS) [16–18]. CRNS is a valid and robust alternative, offering many advantages: it is contactless, allows quantification of soil moisture averaged over large areas with only one probe, and is not invasive for field agricultural operations. The major advantages of CRNS are its large horizontal footprint (up to tens of hectares) and the penetration depth of tens of centimeters, enough to reach typical roots' depth [19,20].

The technique is based on the natural neutrons detected on the earth's surface, that are mostly generated by cosmic rays, according to various processes. The high energy protons component of cosmic rays, produced by galactic sources, interact with atomic nuclei in the upper atmosphere and produce secondary high-energy particles cascades. Muons and fast neutrons are constituents of such cascades. The secondary neutrons reach the ground level and interact with soil atoms. Another mechanism of neutron production is the so-called spallation effect, due to high-energy secondary muons interacting with ground atoms.

Hydrogen in water molecules becomes the dominant factor for slowing down and absorbing neutrons (also known as neutrons moderation). The fast neutrons, produced in air and soil, travel in all directions within the air–soil–vegetation continuum and therefore an equilibrium concentration of neutrons is established. The equilibrium is shifted in response to changes in the water presence above and below the land surface. For example, a drier soil, having a lower moderation capacity, reflects a greater number of neutrons compared to a more humid soil. In the latter, neutrons are more easily moderated, thus slowed down and partially absorbed; the net effect is an increase of the slow population, in respect to the fast one. The resultant neutron intensity above the land surface is inversely proportional to soil water content.

The portion of the neutrons energy spectrum that is most sensitive to soil moisture is the epithermal/fast region from energies of 0.25 eV to 100 keV [20]. Evaporation neutrons from 100 keV to 10 MeV give additional information especially for snow measurements [21]. Finally, high-energy neutrons over 10 MeV are not dependent from local conditions and are directly proportional to the primary incoming flux. Many studies relied on the performance of a set of CRNS probes for monitoring [22,23], modeling [24,25], or remote-sensing validation purposes [26,27].

It is important to underline that the measured intensity of environmental neutrons depends not only on the water in the soil but also on the incoming cosmic-ray neutrons flux [28]. This component changes with changing atmospheric conditions and also with variation of the incoming flux of galactic cosmic rays [17]. For this reason, on one hand CRNS is typically equipped with sensors for air pressure p, air temperature T, and relative humidity h_{rel}. On the other hand, it is worth noting that normally the correction by the incoming-flux is not directly measured in situ, but it is extrapolated offline using the Neutron Monitor Database (NMDB) [29], which provides data from several stations around the world.

The aim of the present study was to present and assess a new sensor for detecting soil moisture based on the CRNS approach. For this reason, several tests have been conducted in different agro-environmental conditions in comparison to current commercial CRNS probes and point-scale soil moisture measurements. The discussion focuses particularly on the applicability of the new sensor for agricultural applications.

2. Materials and Methods

2.1. Instrumentation

For many years neutrons have been detected using ^{3}He proportional counter tubes (for the thermal component) and liquid/plastic scintillators (for the fast component); these two well-established technologies show some important limitations in practical applications. ^{3}He is a nuclide produced almost entirely in artificial contexts, as the product of the tritium decay. The current storage is depleting, and the price is high and rising, since it comes mainly from the production or dismantling of nuclear weapons of past decades [30]. Liquid/plastic scintillators are often made of toxic or hazardous materials, safely used in research contexts, but not suitable for agricultural, civil, or industrial applications. The interest in neutron detection for homeland security applications has triggered, in the last decade, the development of new detectors made up of liquid or plastic scintillation materials with low toxicity, that are safe and easy to use.

We studied a new solution [31], namely Finapp, based on a composite detector made of commercial detectors: EJ-299-33A and EJ-420(6), both manufactured by Eljen Technology (Sweetwater, TX, USA). EJ-420 and EJ-426 are inorganic scintillators, that have proven to have a good response to thermal neutrons [32]. EJ-299-33A was the first plastic detector to become commercially available for gamma/fast-neutron discrimination [33]. The discrimination capability of neutrons from gamma-rays is a fundamental prerequisite, in order to discriminate neutrons from the naturally occurring gamma-ray environmental background, that is not correlated to soil moisture in the same way as neutrons.

We assembled the composite detector by wrapping the plastic scintillator EJ-299-33A (a cylinder of $3'' \times 3''$) with thermal neutron detectors. In the plane face we used an EJ420 detector with a diameter of $3''$. On the lateral face we used EJ426, which has a lower efficiency but is flexible. The optical-grade rubber EJ-560 ensures proper optical contact between the different detectors. A single photomultiplier (PMT) Mod. H6553 (Hamamatsu Photonics, Hamamatsu, Japan) was used to collect light emissions of the scintillators. Figure 1 shows an exploded view of the assembly.

Normally EJ420(6) and ^{3}He tubes are able to detect only thermal neutrons with energy below 0.025 eV but, according to Kohli et al. [20], the most sensitive part to soil moisture of the neutron spectra is the epithermal region between 0.025 eV and 100 keV. In order to collect these neutrons, detectors are normally equipped with a few cm of polyethylene, a material enriched with hydrogen that acts as a moderator slowing down neutron energy from the epithermal/fast region to the thermal region.

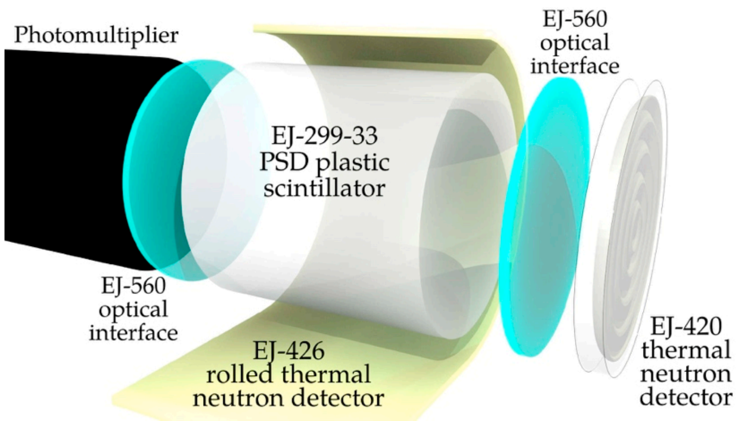

Figure 1. Assembly of the detector, Finapp, to employ in cosmic-ray neutron sensing (CRNS) technique. Abbreviation: PSD, pulse shape discrimination.

2.2. Data Acquisition

The data acquisition system (DAQ) was composed of an electronic signal digitizer model DT5790 (CAEN Spa, Viareggio, Italy) featuring: two input channels, that generate digital waveforms from the analog signals, with a 12 bit resolution and a sampling rate of 250 MS/s (samples per second); and two channels of high voltage power supply, for the photomultiplier. The digitizer is interfaced with a low-cost, low-power, embedded computer (Beaglebone Black). The software controlling the digitizer is an open-source, distributed data acquisition system, called ABCD [34,35] developed for the H2020 C-BORD project [36,37]. ABCD is employed to provide a continuous stream of data to a custom analysis system, based on the group's experience developed during the FP7 TAWARA_RTM project [38]. The analysis is fully automatic and performed online. The probe was equipped with internal temperature sensors and was configured to gather weather data from a local weather station installed near the probe. The operating negative voltage for the photomultiplier was set at 1600 V. Data transmission was ensured by a cellphone modem and data were stored locally in a Secure Digital (SD) memory. Figure 2 shows a block diagram of the probe functionality.

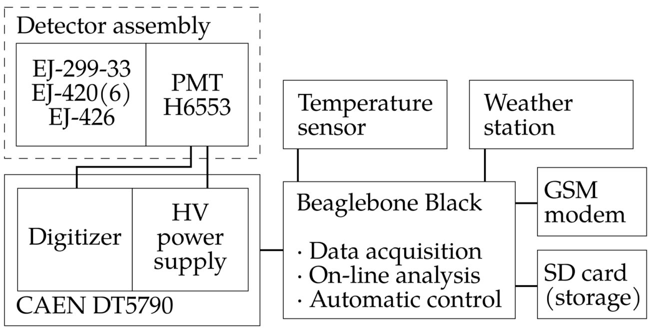

Figure 2. Block diagram of the data acquisition chain of the probe. Abbreviations: PMT, photomultiplier; HV, high voltage; GSM, protocol for data trasmission; SD, Secure Digital.

2.3. Data Processing and Analysis

2.3.1. Particle Discrimination

The significant parameters (e.g., signal integrals), needed for the signals' identification and discrimination, are extracted from the digital waveforms acquired by the digitizer. Together with the auxiliary sensors' data (e.g., temperature, pressure, etc.), the analysis software performs a data merge of the information, in order to correct the parameters and improve the signals identification and discrimination capabilities. Particles are identified and discriminated according to the generated signals, with an algorithm based on the most popular method of pulse shape discrimination (PSD) [39]. This technique exploits the different processes activated by different particles interacting in the scintillator; in particular, the produced light has usually two or more components, characterized by their decay time τ_i. The various light components are excited with different yields, depending on the interacting particle. These processes lead to different waveform shapes, that can be distinguished calculating the so-called PSD parameter, defined as:

$$\text{PSD} = (\text{Long Integral} - \text{Short Integral})/\text{Long Integral} \tag{1}$$

where "Long Integral" is the PMT signal charge-integrated over a long integration gate, while "Short Integral" is calculated on a short integration gate. The "Long Integral" is associated with the light coming from all the components. The "Short Integral" accounts only for the light associated with the fastest component.

Figure 3 shows the typical sampled signals from gamma-rays, fast neutrons, and thermal neutrons (Figure 3a) and PSD parameter versus energy (Figure 3b). Discrimination between particles can be made simply by selecting the significant regions, on the PSD plot, in order to separate the three contributes (Figure 3b).

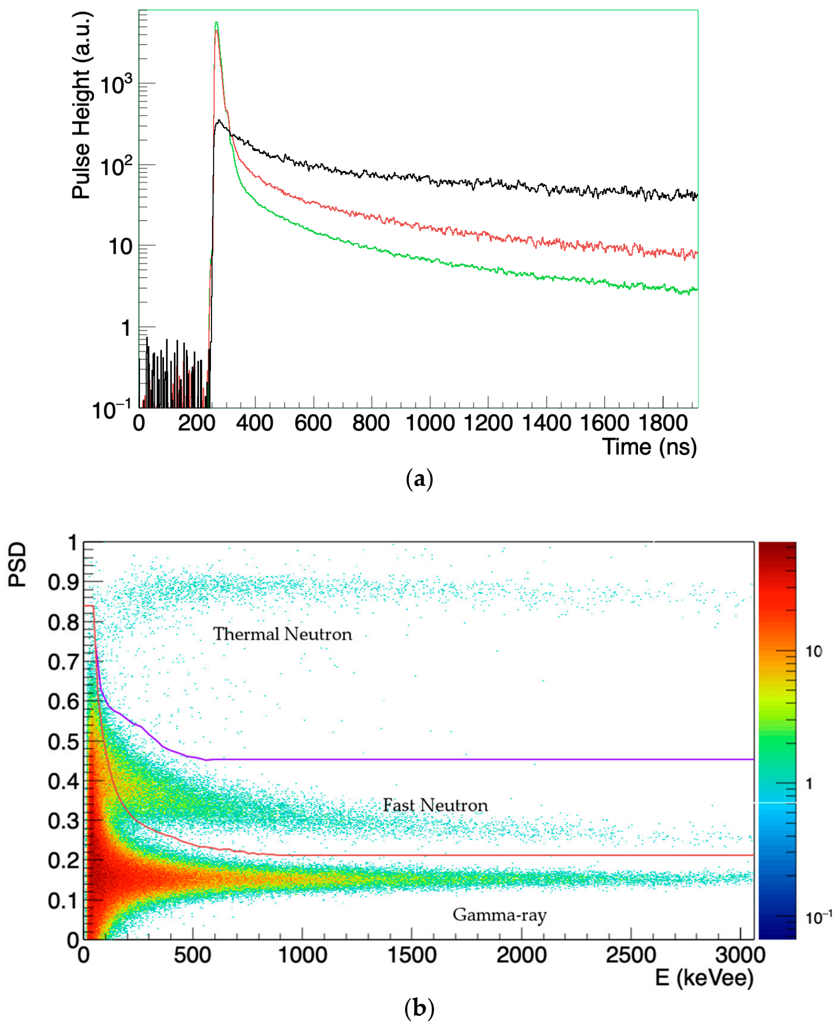

Figure 3. (**a**) Characteristic signals from gamma-ray (green), fast neutron (red), and thermal neutron (black). (**b**) PSD parameter versus energy; different zones are identified by a polynomial line.

2.3.2. From Raw Neutron Counts to Soil Moisture Estimation

The number of neutrons depends not only on the water content in the environment but also on atmospheric conditions and incoming galactic cosmic rays [17]. For this reason, data from a close by weather station was used to normalize neutron counts.

The standard procedure [40] to correct neutron counts (N_{raw}) by atmospheric variations and incoming fluctuations follows:

$$N = N_{raw} \cdot exp\Big(\beta\big(\langle p\rangle - p_{ref}\big)\Big) \cdot \Big(1 - \alpha\big(\langle h\rangle - h_{ref}\big)\Big) \cdot \left(1 + \gamma\left(\frac{I_{ref}}{I} - 1\right)\right) \tag{2}$$

where, h is the absolute humidity in g·m^{-3}, I the incoming flux of galactic cosmic-ray, β = 0.0076, α = 0.0054, γ = 1, and h_{ref}, p_{ref} are the mean value of humidity and pressure during the measuring period, respectively. I_{ref} is the average value of the incoming fluctuation over a long period and depends on the efficiency of the station used for correction.

The corrected environmental neutrons at ground level are converted into (soil) water equivalent θ with the following empirical formula:

$$\theta(N) = \left(\frac{0.0808}{\frac{N}{N_0} - 0.372} - 0.115 - \theta_{offset}\right) \cdot \rho_{bulk} \tag{3}$$

where, ρ_{bulk} is the soil bulk density (kg·m^{-3}), N is the corrected neutron flux, θ_{offset} is the gravimetric water equivalent of additional hydrogen pools (e.g., lattice water, soil organic carbon), and N_0 is the counting rate over dry soil [21,41]. N_0 could be calibrated based on independent soil sampling campaigns as suggested in different studies [18]. Since the aim of the present study was to assess the capability of the Finapp probe to provide the correct hydrological behavior, N_0 was used as a tuning parameter to fit the soil moisture dynamics measured by point-scale measurements.

Concerning the incoming corrections, the standard procedure foresees the use of the nearest Neutron Monitor Database (NMBD) station close to the site measurement, but this this could introduce problems: (i) the distance between the CNRS probe and NMDB stations may be of the order of several hundreds of km; (ii) delays in collecting data from the NMDB can create problems for online monitoring; (iii) dependence from an external source of information, the availability of NMBD data is at the discretion of the institution that maintains the station. To overcome these problems, our probe measured the incoming fluctuations directly in situ through the measurement of muons. Their flux at sea level depends on atmospheric conditions and incoming cosmic-ray fluctuations, in the same way as high-energy neutrons. Muons release a great amount of energy in plastic scintillators; thus, it is possible to identify these particles by putting an appropriate energy threshold to exclude completely the contribution of gamma-rays from the environmental background.

3. Experimental Sites

3.1. Potsdam, Germany

The first experimental site was at the campus of Potsdam University, in the Brandenburg region near Berlin, Germany. This experimental site was mainly dedicated to the assessment of the capabilities of the Finapp probe, based on the comparison with two ^{3}He tubes installed in the field. The two tubes were from Hydroinnova LLC (Albuquerque, NM, USA) and Canberra Industries, (Meriden, CT, USA): two commercial CRNS probes used as a standard for cosmic-rays neutron sensing for many years.

Figure 4 shows test-site pictures. Our innovative detector Finapp measures neutrons in the same energy range of the commercial tubes without the use of ^{3}He gas. In a two-month period of outdoor field tests (from 29 May 2018 to 17 July 2018), Finapp was compared with the Hydroinnova CRS-1000 and the CANBERRA tube. The experimental site is equipped with a standard weather station that was extended to monitor four soil moisture profiles based on point-scale soil moisture sensors (5TE Meter group) installed at 5, 15, 25, and 35 cm depth that are used for comparison.

The climate in Potsdam is warm and temperate, with an average temperature of 9.2 °C and an annual rainfall of 600 mm evenly distributed throughout the year. During summer months, thunderstorms are frequent. The WGS84 coordinates of the installation site are N 52.410087, E 12.978808. There are no cultivated fields nearby; the probes have been installed on an uncultivated grassy lawn.

(**a**) (**b**)

Figure 4. (**a**) Campus of Potsdam University, red point is where CRNS probes were installed and the red circle is the footprint. (**b**) Picture of the installation.

3.2. Lagosanto, Italy

The second experimental site was located in Lagosanto, Italy, in an experimental field in the Porto Felloni agricultural company. This company is renowned as being one of the most technologically advanced in Italy, with a continuous and effective implementation of precision farming practices. The area is located in Emilia Romagna, a few km from the sea and 50 km from Ferrara. The climate is warm and temperate with an average temperature of 14 °C and an annual rainfall of 600 mm, with a dry period during the summer months. The probe was installed in a recent orchard with walnut trees, characterized by a small trunk. During summer months water is provided daily by drip irrigation. The probe was positioned as shown in Figure 5a at WGS84 coordinates N 44.752756, E 12.134761. The probe's footprint is an area with a radius of about 150 m, as highlighted by the red circle. Figure 5b shows a picture of the installation; the probe was installed 1.8 m from the ground. At about 90 m from the probe, five classical Sentek sensors for soil moisture were installed at 10, 20, 30, 40, and 50 cm depth, while a weather station was installed less than 1 km from the probe. Data were collected from August 8, 2018 to November 11, 2018.

In the test area, soil is in general homogenous, and characterized by a sandy loamy texture, with a 2% organic matter, as reported in Table 1.

Table 1. Texture of the soil where the Sentek probes were installed.

Loam	Sand	Clay	Organic Matter	ρ_{bulk}
42.1%	38.5%	19.4%	2.1%	1.4 g/cm^3

(**a**) (**b**)

Figure 5. (**a**) Field site, red point is where the Finapp probe was installed, the red circle is the footprint, the orange point represents where the five Sentek probes are installed at different depths, and the light blue line is the drainage canal. (**b**) Picture of the installation.

The drainage of the soil favors infiltration, calling for the need of frequent irrigation. The plant is vulnerable to dehydration and the soil must therefore always be kept damp, but waterlogging must be avoided, as this can cause asphyxia and blossom-end rot of the fruit.

A particularity of this site is the presence of a very shallow saturated zone. The territory is a reclamation area, kept dry thanks to water pumps that operate 24 h a day. This creates a very shallow saturated zone that reaches 50 cm deep. This is clearly visible from Figure 6, where the soil moisture sensors from the Sentek probes reaches 50% of the water equivalent at a depth of 50 cm. Furthermore, the owner of the property has underlined how the nearby reclamation canal (identified in Figure 5a with the light blue line) creates infiltrations in the field and this creates problems of asphyxiation of the plants due to too much water in the soil.

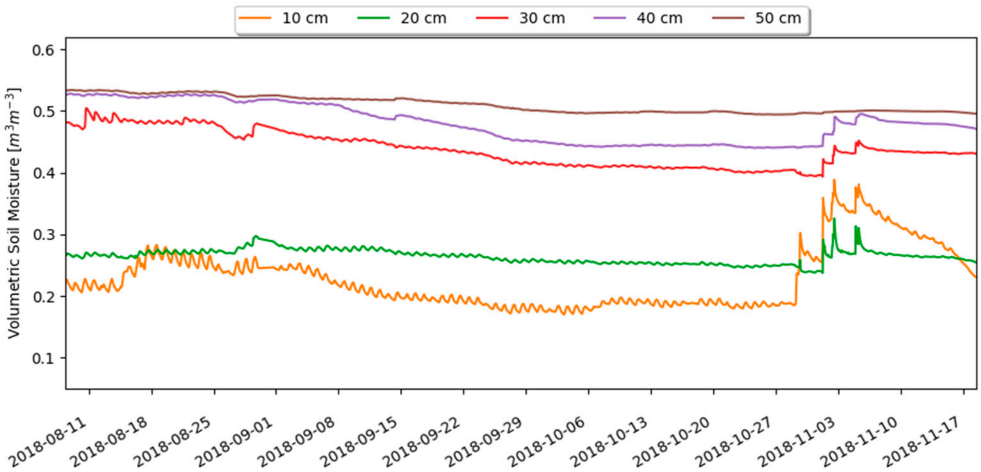

Figure 6. Volumetric soil moisture from Sentek sensor in Lagosanto for the field test period, from from August 8, 2018 to November 11, 2018.

4. Results

4.1. Potsdam Results

The Finapp probe was compared with two commercial CRNS probes, one from Hydroinnova (CRS-1000) and another from CANBERRA during the two months of outdoor testing at Potsdam University. Figure 7 shows the time series of epithermal neutron counts corrected for air pressure, for the whole study period. The neutron counts are averaged over 12 h intervals. The *y*-axis reports the variation in respect to the average counts of the single probes in the whole period.

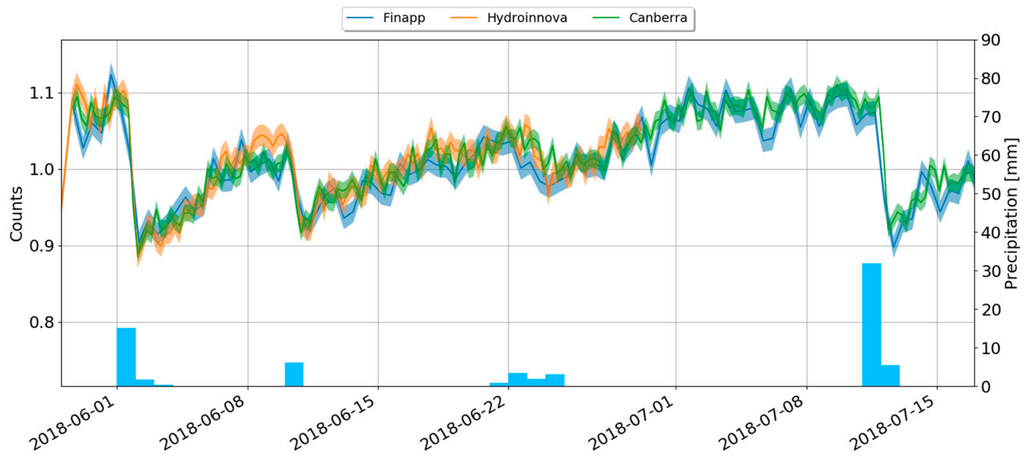

Figure 7. Epithermal counts: Finapp (blue), CRS-1000 from Hydroinnova (orange), and He-3 tube from CANBERRA (green). Data is corrected for atmospheric pressure variations. The colored zone indicates statistic uncertainty. Daily rain is reported in the bottom part of the plot.

Results show very good agreement between epithermal counts. The epithermal neutron counts drop during rain periods when the soil moisture increases. The efficiency of Finapp in respect to CRS-1000 from Hydroinnova, quantified in terms of epithermal counts, was 55%. This aspect means that the Finapp probe needs about twice the time, needed by the Hydroinnova probe, to have the same accuracy in measurements.

Figure 8 shows soil moisture from neutrons count by Equation (3) using data from the Finapp probe. The same figure reports the measurements of classical TDR probes at different depths. It is possible to note that the soil moisture in Potsdam is more uniform at different depths, compared to the Lagosanto data (Figure 6) where the soil moisture increases sensibly with depth. At Potsdam, the soil is much drier and the groundwater system is much deeper, thus it does not affect the conditions in the first 50 cm of the soil.

There is very good agreement between the three rain events (stormy) on June 1, June 11, and July 12. It is worth pointing out the rain event between June 21–26, where light rain increased the soil moisture according to CRNS, but it was not seen from 5TE probes. The behavior could be explained by the small amount of rain which did not infiltrate into the soil but remained on the land surface. For this reason, the 5TE did not record the event while the Finapp detected the water canopy interception or ponding water in the surrounding urban areas. Similar behaviors have been identified in previous studies [40,42].

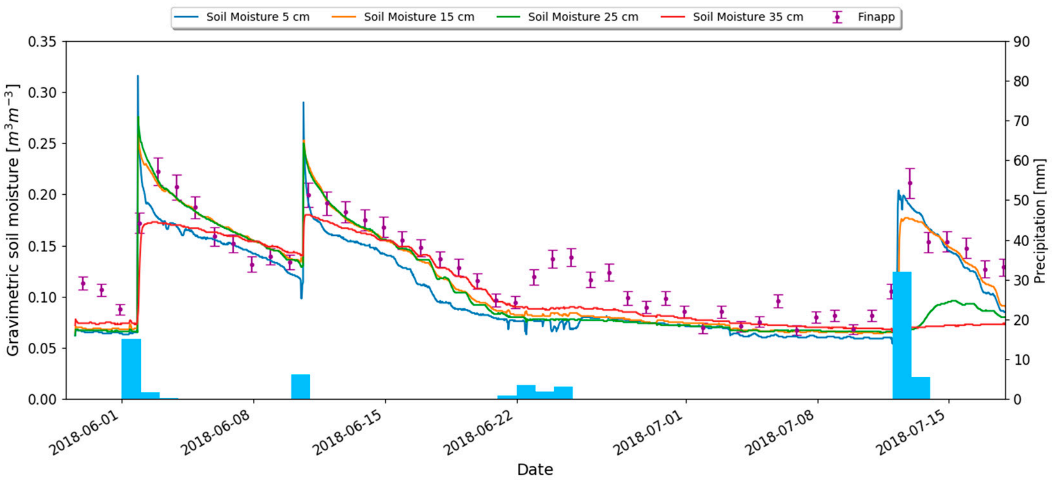

Figure 8. Gravimetric soil moisture from classical time domain reflectometry (TDR) probes (blue, orange, green, red) at different depths. The magenta points are CRNS gravimetric soil moisture using Desilet formula [19] and epithermal counts from Finapp. Daily rain is reported in the bottom part of the plot.

4.2. Lagosanto Results

Raw thermal counts were corrected hourly by absolute humidity and pressure from the near weather station. The reference values were set to h_{ref} = 12 g/m^3 and p_{ref} = 1016.4 hPa. The incoming variation was corrected by the muons measured by Finapp. The flux is mostly stable during the whole period and fluctuation is of the order of 2%. The reference value was set to I_{ref} = 4667.

Furthermore, to improve the comparison with point-scale probes, we computed a weighted average of the measurements (Figure 6) at different depths as described in [43]. CRNS measures the water content in the first 20–70 cm of the soil depending on soil moisture; the higher the water content, less the depth sensitivity, because wet soil has a larger moderation power for neutrons. Finapp acquired data during the second part of summer and first part of autumn.

The end of the vegetative season for the orchard is in September and the irrigation drip was stopped on September 1. September and October were relatively dry months with a rainfall of 60 mm. From October 27 a rainy period significantly increased the soil moisture. Figure 9 shows the averaged soil moisture from the Sentek probe and the soil moisture from Finapp; the lower part of the figure shows the cumulated precipitation with a 24 h interval. Focusing attention on the Finapp data, it is possible to notice a very good agreement between precipitation and soil moisture. Every rain event corresponds to an increase in volumetric soil moisture. Only the events on October 13 report an increase of soil moisture without any precipitation. This increase is probably due to infiltration from the near reclamation canal, that increased soil moisture in the footprint of our probe, as suggested by the property owner. On the contrary, there are some differences if we compare Finapp with point-scale probes. First of all, during the irrigation period the point-scale measurements are less sensitive to precipitation because the drip irrigation biases the point measurement due to a heterogeneous water distribution. In September there is good agreement between the Finapp and Sentek probes; the soil moisture decreases in both cases due to the dry period. In October there is again some discrepancy, probably due to a malfunction of the Sentek probe. The property owner notes that in October the probes are no longer checked daily because the data is no longer used, and periods of malfunctioning occur due to various technical problems (power, batteries, data transmission, etc.). In November the agreement is good again and both the Sentek and CRNS probes respond to precipitation in the same way.

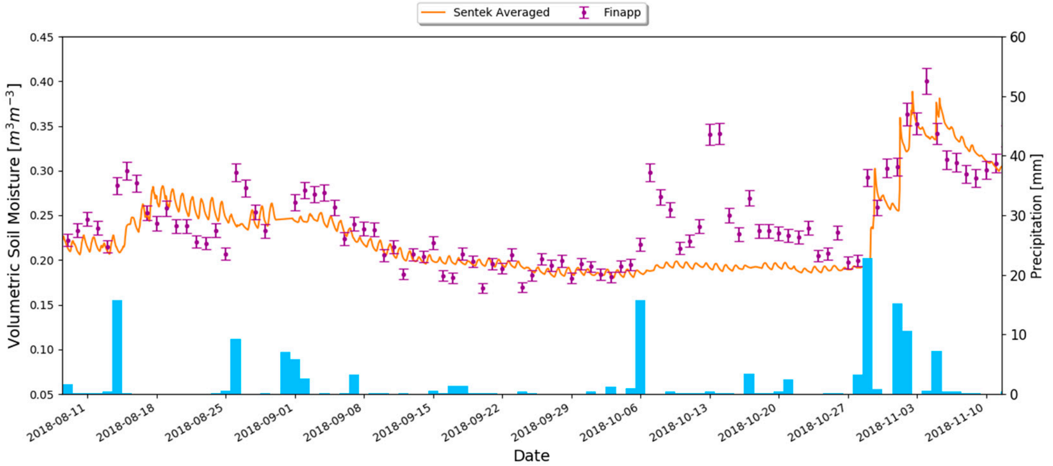

Figure 9. Volumetric soil moisture from Finapp (magenta) and average soil moisture from Sentek (orange); for details see the text. Daily rain is reported in the bottom part of the plot.

5. Discussion and Conclusions

The Finapp probe was tested as a novel sensor for soil moisture estimation over a large area. The sensor makes use of the CRNS technique to reconstruct soil moisture from environmental epithermal neutron counts. The results show that Finapp measures the neutrons in the epithermal region like the well-tested ^{3}He tubes. Efficiency as an epithermal neutrons counter is 55%, in respect to the commercial CRS-1000 from Hydroinnova. Efficiency could be increased, in order to reduce statistic uncertainty, by growing the size of the detector and/or using new materials for thermal neutron detection. In particular, good results were achieved by our group [44] and more research is currently underway.

We reconstructed soil moisture in Figures 8 and 9 for the Potsdam and Lagosanto field trials, respectively. Data is well correlated with precipitations, and it shows the limit of classical point-like measurements, that can be influenced by the heterogeneity of the soil and/or the irrigation distributions. Averaging soil moisture over a large area overcomes the problem of these heterogeneities, making the measurement better suitable for supporting agricultural management conducted at field scale (e.g., irrigation). The soil moisture in Figures 8 and 9 have a time-interval of 24 h between data points. We use such integration time in order to reduce statistic uncertainty on the final measurements. Typical integration values for CRNS commercial probes are 6 or 12 h.

In respect to the currently-employed technology with ^{3}He tubes, Finapp offers more measured parameters, like gamma-rays and fast neutrons. Future development foresees the analysis of this information. In particular, gamma-rays were found to be correlated to soil moisture as well [45,46], but with a smaller footprint. The fast neutrons and high energy events detected can be used to normalize the incoming galactic fluctuations directly in-situ with the data from the sensor.

Overall, Finapp uses non-toxic and non-carcinogenic plastic materials, is easily recyclable, and its technology can be easily scaled to market size. Scalability will be the key point for future development, in order to reduce the price to the same level as professional point-scale soil moisture probes currently on the market.

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