Towards the optimization of a scintillator-based neutron detector for large non-invasive soil moisture estimation

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***Abstract*—Cosmic-ray neutron sensing (CRNS) has been established as a reliable method to estimate non-invasively field average soil moisture. Most of the detectors are, however, based on expensive or toxic materials providing some limitations for a wider application of the method. In this study we further test and develop a new neutron detector based on composite scintillators specifically designed for agro-hydrological applications called CRNS-Finapp. It is shown that the probe is very sensitive to the temperature, however, the effect can be easily compensated by the high voltage module embedded in the probe. Field experiments conducted at a vineyard also support the capability of this new detector to be integrated in long-term observation networks. Further developments will focus on improving the efficiency of the neutron counting rate, on the reduction of the power consumption and on the communication protocols for the transmission of the data.**

Keywords—Soil moisture, proximal sensing, cosmic-ray, neutron

I. Introduction

Soil moisture plays a crucial role in controlling the partitioning of water and energy fluxes at the land-surface [1]. For this reason, the study of this variable is of primary importance in many applications, ranging from weather prediction [2] to irrigation management [3]. Soil moisture, however, shows high spatial and temporal variability [4] and its correct characterization remains an active research topic in different scientific disciplines.

On the one hand, soil moisture is traditionally estimated by means of buried sensors with small support volume (typically smaller than 100 cm^3). Examples are Time Domain Reflectometry (TDR) techniques or capacitance sensors. Such systems have been successfully used in many applications but some difficulties have been recognized in their maintenance for long-term applications and related to the representativeness of the measurements due to the high spatial heterogeneity of soil conditions [1], [5]. On the other hand, remote sensing methods like microwave radiometers, synthetic aperture radars, scatterometers and thermal methods emerged as alternative approaches to provide soil moisture information over large areas [6]. These soil moisture products showed great potentiality in many applications [7] but some challenges remain related to the shallow soil layer detected (few centimeters), the vegetation effect on the signal and the spatial and temporal resolutions [8], [9].

In the last decade, several technologies have been developed and tested to overcome the limitations described above and to fill the gap of current methods [10], [11]. Specifically, the new detectors aimed to estimate non-invasively high-temporal resolution soil moisture and covering the intermediate field spatial scale of hectares. Examples are the terrestrial gravimetry [12], the use of Global Navigation Satellite Systems [13], ground-based microwave radiometry[14] and gamma-ray spectrometry [15].

In this context, the so-called cosmic-ray neutron sensing (CRNS) has emerged as one of the methods to cover the scale gap and overcome most of the limitations of previous approaches [16]. This method is based on the detection of natural epithermal neutrons generated by cosmic-ray fluxes that are inversely correlated with the abundance of hydrogen at the land-surface. The detector is normally placed at 2 m above the ground and the signal is sensitive to the soil moisture dynamic within a footprint of hectares and down to several decimeters below the ground [17], [18]. Originally developed for soil moisture measurements, CRNS has shown also promising applications for the estimation of biomass [19]–[21] snow [22], and canopy interception [23].

The neutron measurements are generally performed based on moderated proportional counters filled with Helium-3 or Boron. The moderation is created by adding shielding material (mostly polyethylene) around the counter. However, lower and lower gas availability, environmental risks, and high costs have motivated the need of alternative technologies for neutron detection in many applications [24]. Among them, plastic scintillator-based neutron detectors have been recognized as a possible longer-term alternative [25]. This detector needs different (and generally more sophisticated) electronics than proportional counters but relies on materials with low toxicity, safe to use and with lower costs. In addition, this detector has the advantage to simultaneously measure other particles like gamma and muons that can be used for further improvements of the method.

Recently, Stevanato et al [26] presented the first results of a new scintillator-based detector called CRNS-Finapp, specifically developed for agro-environmental applications. The study has shown good performance in comparison with commercial proportional 3He gas tube in different conditions, providing the basis for new and wider applications of the CRNS method. The detector is now undergoing several

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improvements aimed at increasing the efficiency in neutron discrimination, reducing the energy consumption, and providing a flexible solution to be integrated in existing monitoring network. In this study, we specifically present and discuss the tests conducted to address the effect of the temperature on the neutron signal.

II. THE SCINTILLATOR-BASED NEUTRON DETECTOR - FINAPP

CRNS-Finapp probe is based on a composite detector made of commercial scintillators manufactured by Eljen Technology (Sweetwater, TX, USA). Specifically, the probe used in the present study combines the inorganic scintillators EJ-426, that have proven to have a good response to thermal neutrons [27], in combination with the plastic scintillator EJ-299 for gamma/fast-neutron discrimination [25].

The probe is equipped with a few cm of polyethylene, a material enriched with hydrogen that acts as a moderator slowing down the epithermal/fast neutrons more sensitive to soil moisture [18]. In addition, a gadolinium shield is added to stop the neutron that are thermalized.

The particles interact with the scintillating matter producing visible photons that are detected by a photomultiplier (PMT) to generate an electric pulse (Mod. H6553 Hamamatsu Photonics, Hamamatsu, Japan). Finally, a data acquisition module is installed based on the digitizer (mod. CAEN DT5725), a low-cost high voltage power supply module (MOD. CAEN A7505) and a single board computer (Beaglebone black). The software controlling the digitizer is an open-source, distributed data acquisition system, called ABCD, specifically developed to perform automatic on-line data processing [28].

The assembly of the probe is shown in figure 1. Further details of the detector can be found in Stevanato et al. [26].

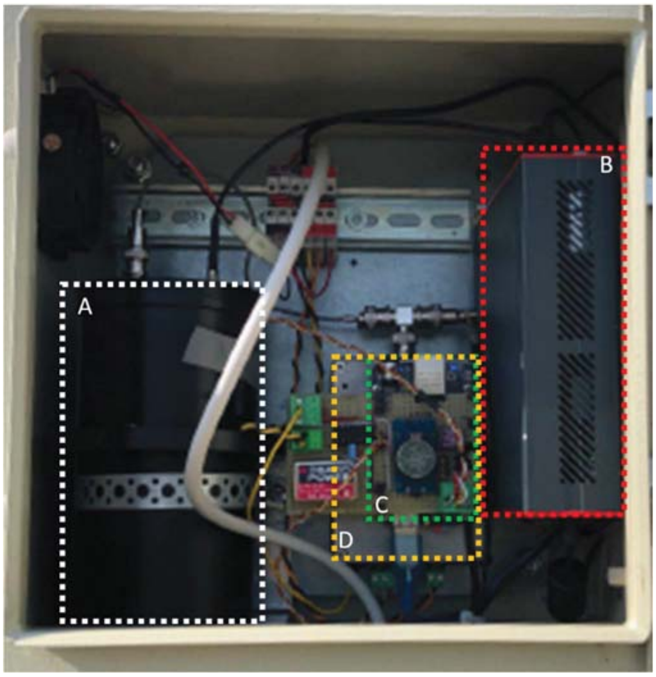

Fig. 1. Assembly of the CRNS-Finapp probe showing all the components embedded in a safety box for outdoor applications: (A) detector and PMT, (B) digitizer, (C) Beaglebone, (D) high voltage module.

III. TEMPERATURE EFFECT ON NEUTRON DETECTION

The scintillators are very sensitive to temperature and the stabilization of the signal can be an issue when the detector is used for environment applications rather than under controlled laboratory conditions. For this reason, the effect of temperature on the signal and electronics is here studied. Specifically, controlled tests were carried out in a climate chamber at a wide temperature gradient (Figure 2 and figure 3). Data collected by the temperature sensor gave evidence of a time needed by the detector to reach the thermal balance of about 3 hours after the temperature setting. For this reason, we discard the first three hours of data in every data acquisition step. Pressure corrected [29] neutron counts rate are then compared (see also eq 1).

First, only the detector and the PMT have been placed in the climate chamber. Results are plotted in figure 2 and show the high sensitivity of the detector to the temperature. Namely, the PMT gain decreases at increasing temperatures. Consequently, the counting neutrons rate decreases. Specifically, a variation of the order of 14% can be noticed.

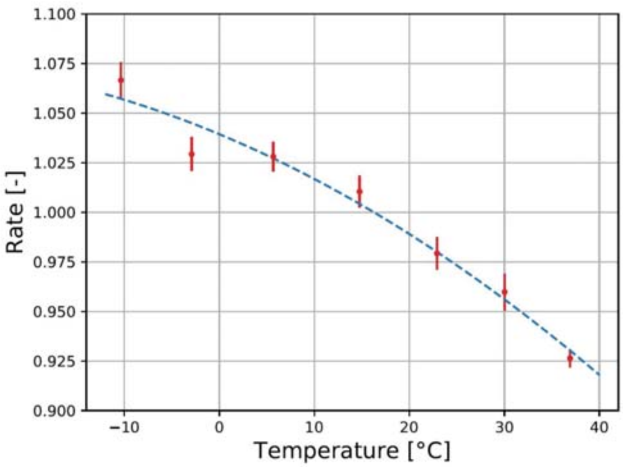

Fig. 2. Normalized neutron count rate as a function of climate chamber temperature. The results have been collected placing only the detector and the PMT in the climate chamber.

For the second experiment, all the apparatus has bene placed in the climate chamber. Thus, in this case, the high voltage module, the digitizer and the Beaglebone are also placed inside the climate chamber in addition to the detector and the PMT. In this configuration we specifically tuned the compensation effect of the high voltage module on temperature. Namely, we decreased the high voltage power supply to compensate the higher gain at low temperature and vice versa. Specific tests were carried out in the climate chamber to quantify the necessary variation of power supply respect to the nominal value to compensate for the efficiency. The results of this second data acquisition are show in figure 3. As can be noticed, it was possible to reduce the fluctuation to less than 3% respect to 14% in the previous case. Some variabilities are still detected but are not correlated anymore to the temperature. Thus, they can be associated to a correlation between the PMT gain and the discrimination algorithm of the different particles. Further tests will be focused on disentangling this behavior.

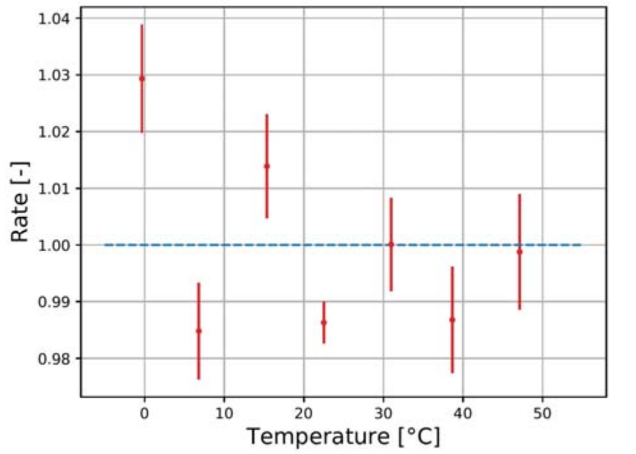

Fig. 3. Normalized neutron count rate as a function of climate chamber temperature. The results have been collected placing all the components of the CRNS-Finapp probe in the climate chamber.

IV. Field Experiments

A. Experimental site

From August 9th 2019 to December 4th 2019, the CRNS-Finapp probe has been placed at Casalserugo, Padova- Italy (coordinates 45 17'21" North, 11 54'13" East). The site is characterized by an average temperature of 14 °C and an annual rainfall of 860 mm, with a dry period during the summer months. The probe was installed at a vineyard irrigated by a drip irrigation system. A picture of the installed probe and of the effective detected area (150 m radius) over which the average soil moisture is estimated are depicted in figure 4. Precipitation data has been taken for comparison from a weather station of the regional environmental agencies (ARPAV) placed at 6 km from the experimental site.

Fig. 4. (upper picture) CRNS-Finapp probe installed at Casalserugo, Padova - Italy; (lower map) the experimental agricultural fields and the effective radius (150 m).

B. From neutrons to soil moisture estimation

The measured neutrons are sensitive to atmospheric conditions and they need to be corrected for the variation in incoming neutrons, air pressure and air water vapor. The standard procedure to correct measured neutron counts (N_{raw}) by these fluctuations follows [29]:

$$f_p = e^{\left(\beta(\langle p\rangle - p_{ref})\right)} \tag{1}$$

$$f_h = \left(1 - \alpha\left(\langle h\rangle - h_{ref}\right)\right) \tag{2}$$

$$f_I = \left(1 + \gamma\left(\frac{I_{ref}}{I} - 1\right)\right) \tag{3}$$

where, f_p, f_h and f_I represent the correction factors for air pressure, relative humidity and incoming fluxes, respectively; h is the absolute humidity in $g{\cdot}m^{-3}$, I the incoming flux of galactic cosmic-ray, $\beta = 0.0076$, $\alpha = 0.0054$, $\gamma = 1$, and h_{ref}, p_{ref} are the mean value of air humidity and air pressure during the monitoring period, respectively. I_{ref} is the average value of the incoming fluctuation over a long period and it depends on the efficiency of the station used for correction. Incoming fluxes have been taken from The Neutron Monitor Database (http://www01.nmdb.eu/nest/). Specifically, data from station Jungfraujoch (Switzerland) has been selected. Air pressure and air temperature time series have been taken from the weather station of the regional environmental agencies (ARPAV).

Based on these correction factors, corrected neutron N are calculated:

$$N = N_{raw} \cdot f_p \cdot f_h \cdot f_I$$

Then, the corrected environmental neutrons N at ground level are converted into soil moisture θ as follows [30]:

$$\theta(N) = \left(\frac{0.0808}{\frac{N}{N_0} - 0.372} - 0.115 - \theta_{offset}\right) \cdot \frac{\rho_{bd}}{\rho_w} \tag{4}$$

where, ρ_{bd} and ρ_w are respectively the soil bulk density ($kg{\cdot}m^{-3}$) and water density ($kg{\cdot}m^{-3}$), 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.

Generally, N_0 is calibrated based on independent soil sampling campaigns, as suggested in different studies [17], [31], [32] and direct measurements are taken for the additional hydrogen pools. Within the present study, N_0 was preliminary tuned to reach realistic soil moisture dynamics. Namely, a value of N_0. = 1150 [neutron counts per hours] has been used. Values for bulk density and additional hydrogen pools have been selected considering the specific soil type and land use (i.e., $\rho_{bd} = 1.30$ $kg{\cdot}m^{-3}$ and $\theta_{offset} = 0.01$ kg kg^{-1}). Better calibration and the assessment of the accuracy of the soil moisture estimation will be the focus of future studies.

C. Temperature effect and soil moisture dynamic

Data collected at the field site is presented in figure 5. Results show that no clear correlation (correlation coefficient r = - 0.49) between neutrons and temperature can be detected despite the wide temperature range (between 0 and 30 °C). For this reason, the results support the capability of the high voltage module embedded in the probe to compensate for the temperature effect on the PMT.

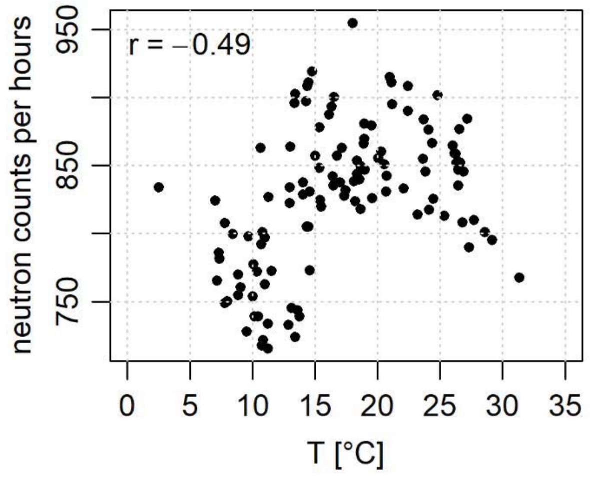

Fig. 5. Comparison between the neutron measured at the field site and air temperature during the period August -December 2019.

The neutrons counting rates are then transformed to soil moisture as previously described. The results are shown in figure 6. The results show that soil moisture well reproduces the expected dynamic. Soil moisture decreases in August with no rain events and a relatively high atmospheric water demand. In contrast, soil moisture increases during the following period characterized by several precipitation events. Some inconsistencies in the dynamics can be explained considering that the vineyard has been irrigated by drip irrigation systems and the rain gauge is located 6 km far from the experimental site. For these reasons, precipitation data does not well represent the local conditions and the actual amount of water that is infiltrated into the soil. Further experiments will be dedicated to collect independent soil moisture measurements to better assess the soil moisture dynamics and the accuracy of the CRNS-Finapp probe.

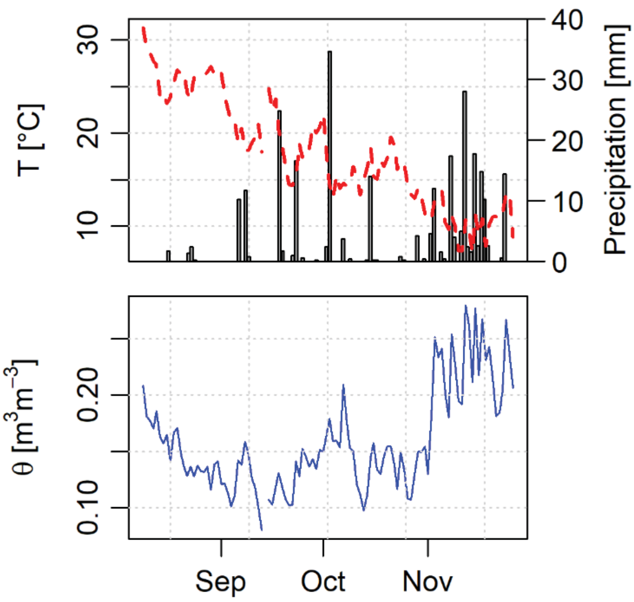

Fig. 6. Time series during the period August and December 2019 of (top) air temperature and precipitation; (bottom) soil moisture estimated with the Finapp-CRNS probe.

V. CONCLUSIONS

The results and the analyses presented in this study confirmed that the scintillator-based neutron detector called CRNS-Finapp is sensitive to temperature variability. However, the high voltage module embedded within the probe was able to well compensate this effect in a wide temperature range. The test conducted at the field experiment also confirmed the capability to remove this effect and to provide a robust soil moisture estimation also at long-term experimental sites and in a wide range of environmental conditions. Further tests and analyses will focus on improving the discrimination of the different particles (gamma, muons), on optimizing the electronics to reduce the power consumption and to provide flexible communication protocols to connect the detector to existing monitoring network.

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