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Study on design, construction and testing of cosmic-ray soil moisture observing system in Vietnam

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Abstract: A new method has been developed in the world called Cosmic-Ray Neutron Sensing (CRNS) for measuring area-average soil moisture at the hectometer horizontal scale. The CRNS principle was based on the measurement of neutrons produced by cosmic rays in air, soil and other materials. These neutrons are moderated by mainly hydrogen atoms located in soil, and emitted into the atmosphere at the scale of hundreds of meters and its density is inversely correlated with soil moisture [3]. The CRNS technique has been known for more than 10 years [21] and validated by many scientific publications in the world. Together with other traditional methods for soil moisture determination such as point measurement and remote sensing, CRNS technique will effectively contribute to the real-time monitoring of drought, prediction of flash floods and landslides, or planning irrigation in smart agriculture. This paper is written to introduce the results of the COSMOS-VINATOM project of the Ministry of Science and Technology. By this project, this is the first time the CRNS technique has been applied in Vietnam, a country greatly affected by global climate change. The cosmic-ray soil moisture measurement method and the design of a specific COSMOS using advanced technologies in neutron and muon detector, signal processing and data transmission are described in this paper. This system has also been tested in the field in Xuan Canh commune, Dong Anh district, Hanoi, Vietnam with initial positive results.

Keywords: *Soil moisture, cosmic-ray neutron, scintillation neutron detector, muon detector.*

I. INTRODUCTION

Soil moisture is expressed as a percentage of the weight of water in the soil to the weight of the soil. Soil moisture is also expressed as the ratio of the percentage of water capacity in the soil to the total volume of the soil. When soil moisture is below a certain limit, plants do not absorb enough water, then drought will occur. Soil moisture is an important parameter in the hydrological cycle and affects many different applications, including agricultural management, monitoring of environmental changes (sandstorms and erosion), climate and weather applications, predicting natural disasters (floods and droughts) and recreating groundwater. At present, there are many traditional methods to measure soil moisture such as drying method, actual volumetric method, specific gravity method, ray method , dielectric property method and so on. Although these methods can accurately estimate the moisture content of soil profile, they are point measurement methods with small measurement scales, and measurement results can only represent the soil moisture status of this point, so spatial

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representation is small. The study of soil moisture monitoring by remote sensing achieved rapid and comprehensive development in the 1970s. Remote sensing technology has advantages such as strong dynamic contrast, long-term dynamic large-area monitoring and good spatial-temporal resolution (Njoku et al., 1996) [25], but it also has disadvantages such as shallow measuring depth, poor penetration, poor sensitivity, and short satellite flight life (Entekhabi et al., 2004 [26]; Andreasen et al., 2016 [27]; Hashemi, 2017 [28]).

It is necessary to have new devices with a wider scale that replace traditional point measuring devices. The use of nuclear and conventional techniques to improve the soil, water, and crop management technologies and practices for sustainable agricultural intensification had been highlighted in the The Soil and Water Management & Crop Nutrition Subprogramme of the Joint FAO/IAEA Division (IAEA-TECDOC-1809) [1]. In the last decade, to overcome the aforementioned operational challenges, a method named cosmic-ray neutron sensing (CRNS) [2, 3, 4] (Figure 1) [6,7] has been developed in order to fill the gap between point-scale and remote sensing approaches. 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 secondary neutrons reach the ground level and interact with soil atoms. Hydrogen in the water molecule is the main factor for slowing down and absorbing neutrons (also known as neutrons moderation). A drier soil with less soil water content, having a lower moderation capacity, reflects a greater number of neutrons compared to a more humid soil with more soil water content. 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 0.025 eV to 100 keV [5]. In addition, the measured intensity of environmental neutrons depends not only on the water in the soil but also on the incoming cosmic-ray neutrons flux. This component changes with changing atmospheric conditions such as air pressure, air temperature, and relative humidity.

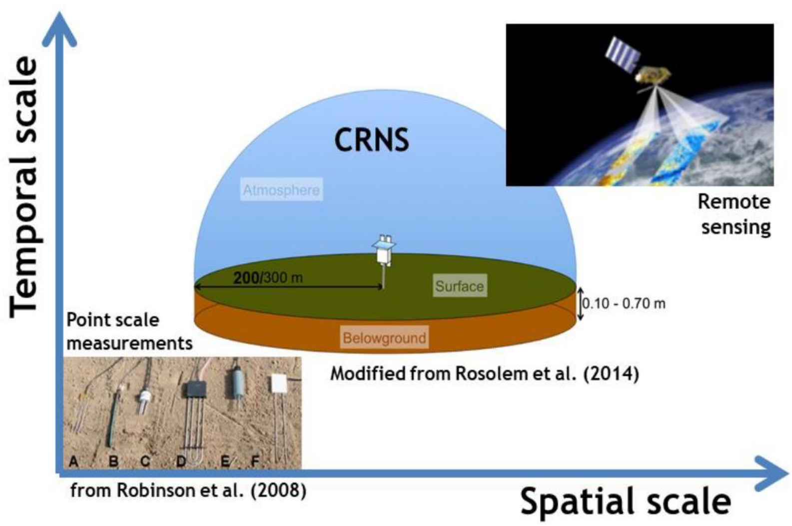

Fig. 1. CRNS technique fills the gap between point-scale and remote sensing [Robinson et al. (2008)][6], [Rosolem et al. (2014)][7]

Many scientists around the world have followed the CRNS, and they have determined the technique to be the most suitable approach for measuring water content at the spatial scale of hundreds of meters in hours. In recent years, the technology of measuring regional soil moisture content using CRNS method has been rapidly developed. In Vietnam, Ministry of Natural Resources and Environment in collaboration with the Ministry of Science and Technology - Vietnam Atomic Energy Institute (VINATOM) has planned to implement the project of construction of a real-time drought monitoring system through COsmic-ray Soil Moisture Observing System (COSMOS). This article presents the first COSMOS-VINATOM system to be researched and manufactured within the framework of the Ministry of Science and Technology project. Advanced technologies in neutron and muon detectors, signal processing and data transmission were used in the system, along with methods of calculation, correction and calibration based on neutron, muon counts and meteorological parameters recorded at the same time at the measurement location for determining soil moisture. The system has also been installed and tested in experimental field located in Xuan Canh (Dong Anh district, Hanoi, Vietnam), along with the actual soil sampling campaign for calibration. Some initial observational results of soil moisture obtained on the system are also presented.

II. MATERIALS AND METHODS

A. COSMOS-VINATOM system design and manufacture

The COSMOS-VINATOM system is designed and manufactured within the framework of the project on the basis of cooperation and partial technology transfer with FINAPP SRL (Italy), quoted by FAO and by IAEA - International Atomic Energy Agency [24]. This is an embedded system for measuring cosmic-ray neutrons in the environment to determine soil moisture. It is made up as shown in Figure 2 with functional modules including: Detector-1 (1) for thermal neutron; Detector-2 (2) for muon; Signal Processing and Data Acquisition Board (3); Solar panel (20 Watt) (5) and backup battery (6). The detectors, electronic units and weather sensors are housed in an IP66 Protection Class box enclosure (4) for outdoor use.

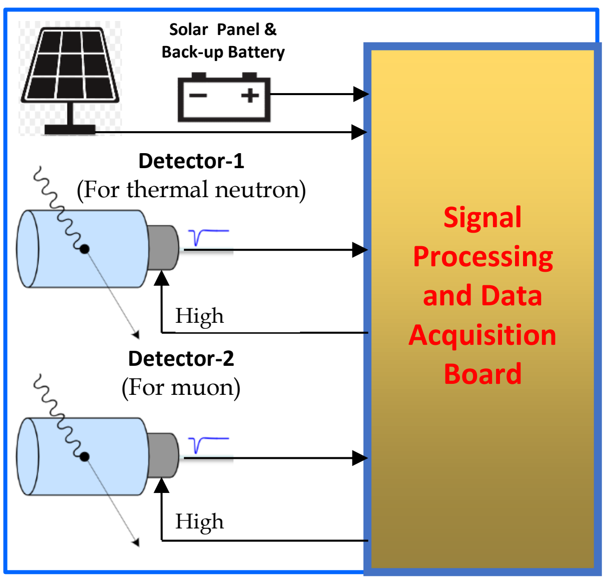

Fig. 2. Function block diagram of COSMOS-VINATOM

1. Detectors

Neutron detector

Commercial instruments such as those from Hydroinnova, USA (www.hydroinnova.com) use traditional ^{3}He gas proportional counters to detect cosmic-ray neutrons. However, due to the global shortage of ^{3}He, the price of this type of detector is high and increasing.The alternative thermal neutron detector (Detector-1) has a compact structure based on scintillator that can detect thermal neutrons with high efficiency and with low sensitivity to gamma radiation. The new detector based on ^{6}LiF/ZnS (Ag) scintillators, which replaces the 3-He gas proportional counter, configured as shown in Figure 3, consists in a layered structure of sheets sensible to thermal neutron and wavelength shifters to collect light through the photomultiplier. The scintillators are formed from multiple layers of ^{6}LiF/ZnS (Ag), each layer has a thickness of 400 µm, EJ-426 [8], featured as table I. The thin sheet which is able to detect thermal neutron consists of a homogeneous matrix of fine particles of lithium-6-fluoride (^{6}LiF) and zinc sulfide phosphor (ZnS:Ag) compactly dispersed in a colorless silicon binder. The lithium is enriched in ^{6}Li to a minimum of 95 atom percent.

The neutron detection process employs the nuclear reaction ^{6}Li (n, α) ^{3}H:

$$^{6}Li + ^{1}n \rightarrow ^{3}H + ^{4}He + 4.78\ MeV$$

with a cross section of 941 barns for 0.025 eV neutrons. The resulting triton and alpha particles are detected by ZnS:Ag phosphor.

Table I. Thermal neutron detector

^{6}LiF:ZnS Mass Ratio	1:3
Thickness	400
Theoretical NTH Efficiency	0.
Light Output (% Anthracene)	300
Wavelength of Maximum	450

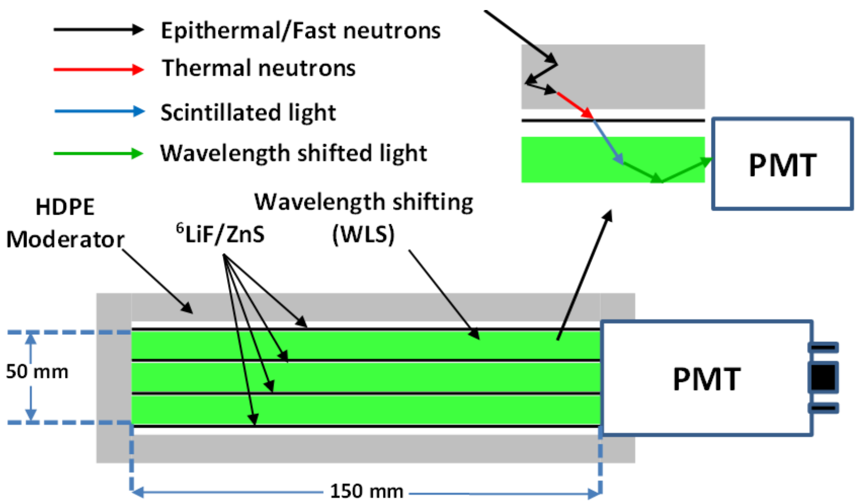

Fig. 3. Structural diagram of the thermal neutron detector

The wavelength shifter is a green-emitting plastic, EJ-280 [9], designed with interlayers of $^{6}LiF/ZnS$ (Ag). The plane provides a compact means of light collection. The green light is effectively turned 90° as a result of the isotropic re-emission and is transmitted by total internal reflection to photomultiplier tubes typed R878-Hamamatsu [10] at the end of the bar to achieve highly uniform light collection. The total neutron detector with the 15x15x5 cm geometry as shown in Figure 4 is embedded in a Polyethylene (HDPE Moderator) box, 12 mm thick, in order to enhance the detection of the epithermal component of the environmental neutron spectrum (approximately 0,5 eV $<E_n<$ 50 keV).

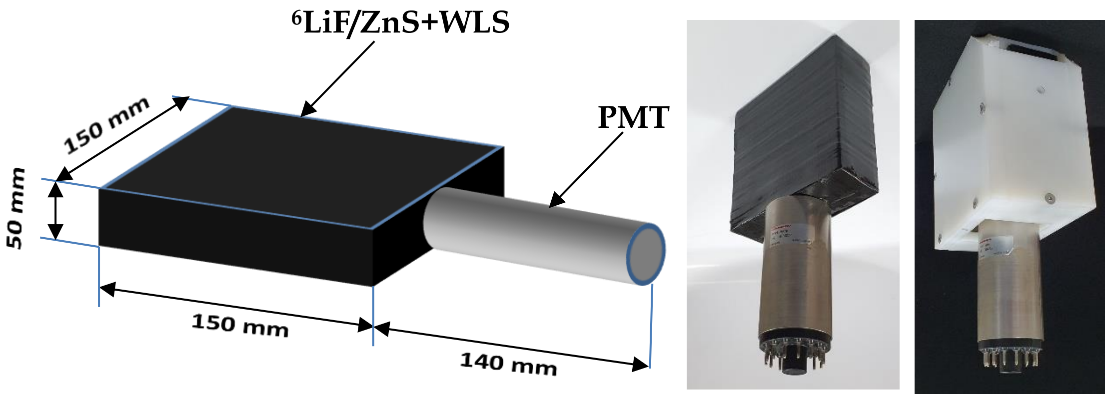

Fig. 4. 3D model and real structure of the neutron detector

Muon detector

A muons detector (Detector-2) is used to monitor any variations of the cosmic ray incoming. It is made up of a cylinder of plastic scintillator 2”x2” typed EJ-200 [11] read by a 1.5” Photomultiplier tube typed R11102-Hamamatsu [12] as shown in Figure 5.

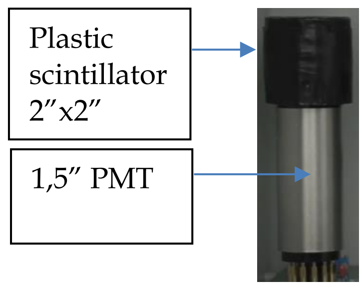

Fig. 5. Muon detector

2. Data Acquisition Board

The *Signal Processing and Data Acquisition Board* has functional components as shown in Figure 6. After passing through the preamp circuit (Preamp) to keep the pulse shape and create a suitable amplitude, the pulse output signals from the anodes of the photomultiplier tubes of the neutron and muon detectors are directly digitized by high precision digitalizations based on ARM Cortex™-M4 STM32L412K8 [13] microcontrollers. These microcontroller-based digitizers with a sampling frequency of 5Ms/s and 12-bit resolution perform the following tasks: pulse shape digitalization; noise rejection; neutron, muon and gamma pulse shape discrimination; counting these pulses at a preset interval; interfacing with the *Central Data Acquisition and Logger* based on ARM Cortex™-M4

STM32L496RE [14] microcontroller. The numbers of neutron and muon counts over a set time are sent from the digitalizations to the data logger where they are recorded. Data are stored in the data logger on secure digital (SD) cards and transmitted via the GSM/4G LTE modem to a data acquisition computer. The COSMOS-VINATOM's data logger also houses temperature, humidity and pressure sensors which are used for instrumental diagnostics and corrections. The power for the instrument is taken from a 12 V DC source, usually a rechargeable battery connected to a solar panel.

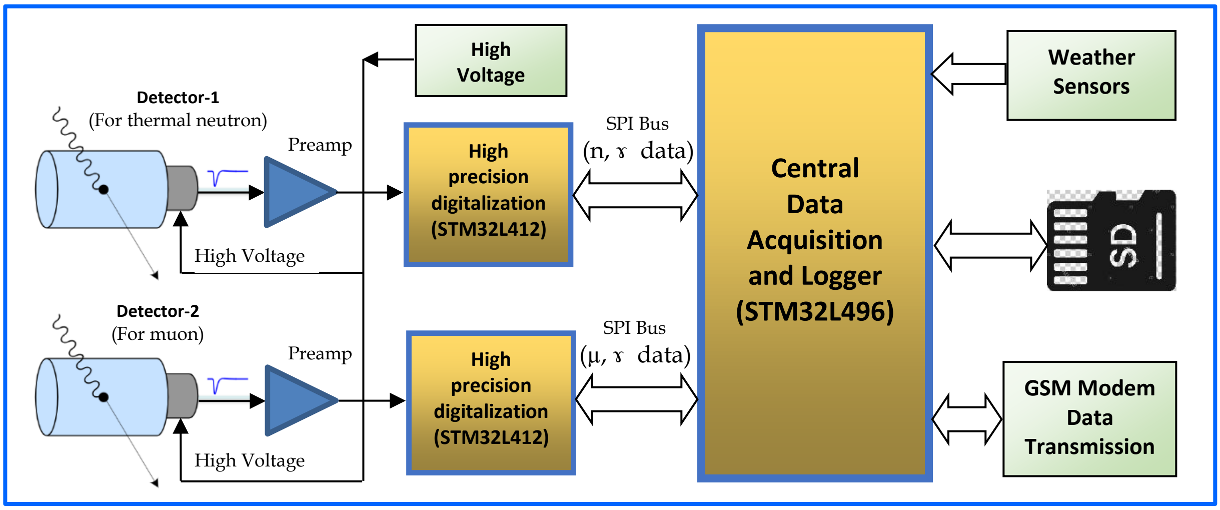

Fig. 6. Functional Block Diagram of Signal Processing and Data Acquisition Board

The main features of the *Signal Processing and Data Acquisition Board* are:

- Operating voltage 9-30 Volt
- Typical power consumption 30mA @ 12Volt
- Two input channels: neutron and muon detectors
- High voltage power supply for photomultiplier (max 1600 Volt –500 μA)
- Dimension 25x12 cm for photomultiplier board and 14x11 cm for main board
- High precision digitalization of the preamplified signal (5Ms/s –12 bit)
- Firmware for particle discrimination
- High precision Atmospheric pressure (sensor LPS22HH)
- Internal temperature (sensor LPS22HH)
- Outside temperature and humidity (sensor SHT20)
- Real Time Clock, accuracy 3 min per year
- Charge controller to operate the board off-the-grid, typically with a small solar panel (20W) and backup battery (7Ah)
- Integration intervals settable from 5 minutes to 6 hours
- Local storage on SD card (up to 32Gb)
- SDI-12 and RS-232 interfaces to connect board to existing data logger
- GSM modem for direct transmission of the data in the CLOUD

The complete COSMOS-VINATOM system is installed 1.8 meters above the ground as shown in Figure 7.

Fig. 7. The complete COSMOS-VINATOM system

B. Data Processing and Analysis

The number of neutrons above the land surface depends not only on the water content in the environment but also on atmospheric conditions and incoming galactic cosmic rays [3]. The standard procedure [15] to correct neutron counts (N_{raw}) for air pressure, air vapor and incoming variability as following factors.

$$f_{bar} = e^{\beta(P-P_{ref})} \quad (1)$$

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

$$f_i = \frac{I_{ref}}{I} \quad (3)$$

$$N = N_{raw} \cdot f_{bar} \cdot f_h \cdot f_i \quad (4)$$

Where, h is the absolute humidity in g.m^{-3}, β = 0.0076, α = 0.0054 (for details see Zreda et al., 2012 [3]; Rosolem et al., 2013 [22]; Hawdon et al., 2014 [23]), and h_{ref}, p_{ref} are the mean value of humidity and pressure during the measuring period, respectively. I is the incoming flux of galactic cosmic-ray and I_{ref} is the average value of the incoming fluctuation over a long period. Concerning the incoming corrections, we used a new method developed by Stevanato [16] as an alternative to retrieving data from Neutron Monitor Database (NMBD) stations. According to this method, since muons are particles created from the same cascade of primary cosmic-rays that generate neutrons at the ground, measuring muon flux by Detector-2 to determine I and I_{ref} will allow to detect incoming cosmic-ray variations locally easily. Therefore, it is possible to determine the soil moisture in real time in a stand-alone system without the requirement of external information and offline data reanalysis. This is a significant improvement over conventional CRNS systems.

Then, corrected neutrons N are converted into gravimetric water content θ_p(g/g) and volumetric water content θ based on Desilets equation [17]:

$$\theta_p = \left(\frac{0{,}0808}{\frac{N}{N_0} - 0{,}372} - 0{,}115 - \theta_{offset} \right) \quad (5)$$

$$\theta = \theta_p . \frac{\rho_{bd}}{\rho_w} = \theta_p . \rho_{bd} \quad (6)$$

Where ρ_{bd} (g/cm^3) is the soil bulk density, ρ_w (1 g/cm^3) is the water density, 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. The value N_0, site-specific parameter, could be calibrated based on independent soil sampling campaign. The precision of the CRNS technique depends mainly on the neutron counting rate, N, which follows the Poisson statistic (Knoll, 2000) [18], in which the standard deviation is simply defined as $\sigma_N = \sqrt{N}$. Applying the error propagation formula [19], the precision of soil moisture determination can then be computed through the function (5), i.e.

$$\sigma_\theta = \sigma_N \frac{\partial \theta}{\partial N} \quad (7)$$

Which yields:

$$\sigma_\theta = \frac{a_1 N_0 \sqrt{N}}{(N - a_2 N_0)^2} \quad (8)$$

COSMOS-VINATOM was developed as a separate component of the overall future COSMOS network plan. According to this network model, individual COSMOS systems send the neutron data and ancillary data (pressure, temperature, relative humidity, voltage) to a server where soil moisture is computed and posted immediately on the COSMOS web site. Data are acquired at one-hour intervals and sent via GSM/4G LTE modem to the COSMOS server where they are processed and placed in the public domain (http://data.cosmos-vinatom.vn).

III. EXPERIMENTAL RESULTS

The experimental site for setting up the COSMOS-VINATOM system is at Xuan Canh commune, Dong Anh district, Hanoi, Vietnam, located by latitude 21°05'44.4"N and longitude 105°51'23.4"E, and elevation of 13 m. This place is an abandoned grassland, located in the tropical monsoon climate with heavy rainfall from May 3 to October 5 and dry weather from October 5 to May 3, with an average temperature of 23.6^{o}C and the average annual rainfall is 1800 mm. The system was installed on September 20, 2022 in Xuan Canh (Figure 8, left) for calibration and field testing.

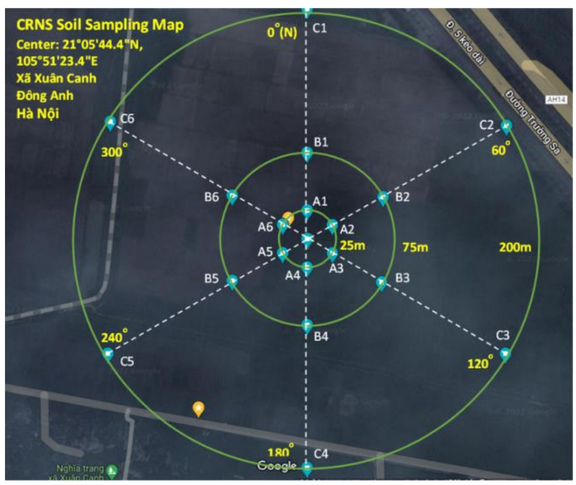

Fig. 8. Xuan Canh-Dong Anh-Ha Noi experimental site, with (left) COSMOS-VINATOM and (right) soil sampling locations and CRNS footprint (200 m radius)

Calibration

The calibration procedure involves obtaining an estimate of the area-averaged soil moisture content over the CRNS measurement footprint by gravimetric sampling and the subsequent neutron intensity. The standard of 108 undisturbed soil samples was taken at three radial rings, extending outwards from the CRNS. The radial rings were situated at distances of 25 m, 100 m and 200 m from the CRNS (Figure 8, right). At each of the three rings, eight points were taken at an equal distance along the circumference of the ring. At each sample point, soil samples were taken at different depths, from 0 cm to 30 cm in 5 cm increments to capture the profiles of soil moisture using a split corer of 30.48 cm length and 5.08 cm inner diameter with stainless steel liners 5 cm in length and 4.9 cm inner diameter. The area-averaged soil moisture content was measured from soil samples taken from the field using the gravimetric method (Gardner, 1986) [20] (i.e., oven dry soil at 105° Celsius for 24/48 hours to a constant soil weight).

The neutron count (N) for the calibration was determined as the average neutron count which the soil samples for that calibration were obtained at the same time from the system. This count was used to determine the N_0 value for the calibration, using the rearranged calibration Equation (5). The calibration datasets, parameters and derived values of N_0 for the COSMOS-VINATOM are available at https://cosmos-vinatom.vn/calibration-data/.
After analyzing the collected soil samples using the method [20], the following results were obtained: the area-averaged soil moisture content ($\boldsymbol{\theta}$) was 0.182 g/g, the dry soil bulk density was ρ_{bd} =1.64 g/cm^3, and the corresponding average number of corrected neutrons ***(N)*** measured by the system was 442 cph on the calibration date in Table 3. From these two values $\boldsymbol{\theta}$ and $\boldsymbol{N}$, the site-specific N_0 value for the calibrations was calculated to be 686.46 cph using the inverse of equation (5). The calculated parameter N_0 is also the neutron measuring efficiency of the system in air above dry soil at a specified location (Xuan Canh) obtained by calibration. This calculated N_0 value was used in the calibration function equation (5) to determine the hourly soil moisture, which is often expressed in units of volumetric water content percent (VWC(%) = $\theta \times 100$). This value (686.46 cph) measured in Vietnam is lower than that measured in Europe (1020 cph) with the same neutron detector configuration in the assessment [31]. This is explained because the geomagnetic cutoff rigidity, which greatly affects the ability of cosmic-ray neutrons to reach the ground, is about 5 GeV in Europe, which is much lower than in Vietnam, which is the highest in the world around 17 GeV [21]. The assessment [31] also shows that at the same measurement site on the same geomagnetic cutoff rigidity, the sensitivity of the neutron detector in the Finapp configuration is 20% more sensitive than Hydroinnova's CRS-1000 commercial system.

Soil moisture results

After calibration, the COSMOS-VINATOM system was tested for certain periods of time to observe the actual soil moisture in the field. Some of the initial results of soil moisture measurement on the COSMOS-VINATOM system include the raw values obtained from the system in Table 2 and the calculated values respectively according to the formulas (1), (2), (3), (4), (5), (6) and (8) shown in Table III. The entire process of obtaining raw data and calculating the final value of soil moisture is carried out automatically on the server and can be observed online in real time at the web-page: http://data.cosmos-vinatom.vn/HOME/Metadata?data=SYNTHETICS, Data Visualisation Chart at: http://data.cosmos-vinatom.vn/HOME/DetailLoc?sn=862531042531534.

Table II. Raw data

Date	**Time**	**Neutrons (cph)**	**Muon s (cph)**	**Intern al Temp. (°C)**	**Extern al Temp. (°C)**	**ur (%)**	**Pressu re (hPa)**	**Absolute Humidit y (g.m^3)**	**Correcte d Muons (cph)**
9/20/2022	9:42	**417**	**1719**	39.7	33.3	68.1	1007.3	24.58	1763
9/20/2022	10:43	**377**	**1655**	40	33.1	66.6	1007.8	23.79	1695
9/20/2022	11:45	**409**	**1698**	41.4	34.6	65	1007.2	25.12	1745
9/23/2022	9:51	**353**	**1693**	38.3	30.5	66.7	1011.7	20.74	1713
9/23/2022	10:52	**348**	**1611**	38.5	31.3	64.7	1011.4	21.00	1633
10/18/2022	11:51	**414**	**1635**	33.1	29.3	35.9	1015.1	10.46	1639
10/18/2022	12:53	**400**	**1648**	35.1	29.7	35.5	1013.7	10.57	1658
10/18/2022	13:54	**396**	**1610**	37	30.2	37.7	1012.8	11.53	1624
10/18/2022	14:56	**408**	**1653**	37.5	30.2	37.3	1011.8	11.41	1671

Table III. Calculated data

Correction Factors				**Corrected Count Rate**	**Final Data (1-h average)**				
Barometric Factor (f_{bar})	**Humidity Factor (f_h)**	**Incoming factor (f_i)**	**Total Factor ($F = f_{bar}. f_h. f_i$)**	**Corrected Neutrons (N.F) (cph)**	**θ_p (g/g)**	**θ (m^3/m^3)**	**θ (%)**	**σ_θ (± m^3/m^3)**	**σ_θ (%)**
0.965	1.133	0.954	1.043	434.95	0.194	0.318	31.8	0.051	15.91
0.969	1.128	0.993	1.085	409.00	0.246	0.403	40.3	0.057	14.21
0.964	1.136	0.964	1.055	431.69	0.200	0.327	32.7	0.051	15.69
0.998	1.112	0.982	1.090	384.70	0.314	0.515	51.5	0.065	12.65
0.995	1.113	1.030	1.142	397.40	0.276	0.452	45.2	0.061	13.47
1.024	1.056	1.026	1.110	459.62	0.157	0.257	25.7	0.045	17.64
1.013	1.057	1.015	1.086	434.60	0.194	0.319	31.9	0.051	15.88
1.006	1.062	1.036	1.107	438.38	0.188	0.308	30.8	0.050	16.14
0.998	1.062	1.007	1.067	435.40	0.193	0.317	31.7	0.050	15.94

The results show that the soil moisture data observed on the COSMOS-VINATOM system is consistent with actual observations at the site, which are correlated with the parameters recorded in the weather history in the measurement area, especially precipitation. They are at specific times as of September 20, 2022: relatively dry soil state, soil moisture measured about 35%; on September 23, 2022 (Hanoi, Vietnam Weather History [29]): soil state after the previous day's rain, soil surface with water, mud, high soil moisture measured by CRNS is about 48.3%; on October 18,2022 (Hanoi, Vietnam Weather History [30]): after 2 weeks without rain and the influence of the northeast monsoon, the soil surface is basically dry, only a few places have moisture, the soil moisture according to CRNS is about 30%. The results in the data table show that the neutron count at the measurement site is inversely proportional to the soil moisture content. As stated above, with the current neutron counting rate about 400 cph, the counting uncertainty is 5% ($400^{-0.5}$). Propagating this counting uncertainty through the calibration function (5), the error in soil moisture according to formula (8) is about 15.28% for One-hours average. Quadrupling the counting time will halve ($4^{-0.5}$) these uncertainties. The error or fluctuation of soil moisture is mainly due to the statistical error of the neutron count over a 1-hour period of about 15%. When the system is later permanently installed for continuous measurement, averaged over a 12-hour period as recommended in the IAEA-TECDOC-1809 document [1] gives an error of less than 5%.

IV. CONCLUSIONS

During the 2-year period of the project, the COSMOS-VINATOM system has been fully designed and manufactured. Research and manufacturing results include: a combination of cosmic-ray neutron and muon detectors using plastic and metal materials, especially lithium-6, that are easy to find, lightweight and much less bulky than the standard on the market while still achieving comparable neutron sensitivity; the electronic equipment system comes with radioactive pulse digital signal processors, wireless data acquisition and transmission according to IoT technology and solar power, allowing the system to operate independently and continuously in the field, providing fundamental advantages in research and application. The software for the acquisition, calculation, storage and presentation of real-time soil moisture data has also been developed based on a web-based platform on the cloud server, allowing users to easily access it via internet.

The system after calibration was initially put into field testing to measure actual soil moisture and gave the positive results in applying CRNS technique in Vietnam. Future long-term soil moisture measurements based on this system will continue to be carried out, along with comparisons with other methods and with precipitation for a complete assessment, so that it can be officially used in areas such as drought warning, smart agriculture in Vietnam.

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