Observation on Soil Moisture of Irrigation Cropland by Cosmic-Ray Probe

Zhongli Zhu, Lei Tan, Shengguo Gao, and Qishun Jiao

***Abstract*—The newly developed cosmic-ray probe (CRP) method for measuring area-average soil moisture at the hectometer horizontal scale was tested in the 2012 observation campaign of the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) in the irrigated cropland area of Zhangye Oasis. As compared with the traditional point observation, data analysis shows that the CRP could measure the real areal soil moisture, except when the water is frozen and during thaw. During the irrigation period, the presence of surface water can lead to an overestimation of the soil moisture. During non-irrigated periods, the CRP has a very strong correlation with the averaged soil moisture of 19 SoilNET probes in its footprint, whose R^2 is 0.73 and root-mean-square error is 0.0275 m^3/m^3. In comparison with the Polarimetric L-band Multi-beam Radiometer (PLMR) retrieved soil moisture, which has a pixel resolution of 700 m, the CRP provides much better results, with a coefficient of determination of 0.96 and 0.64, respectively. The results show that the CRP is a robust area-averaged soil moisture observation method, which can be used to obtain "true" values of field-scale soil moisture for remote sensing validation.**

***Index Terms*—Cosmic-ray probe (CRP), Heihe Watershed Allied Telemetry Experimental Research (HiWATER), soil moisture, wireless sensor network.**

I. Introduction

SOIL moisture is a key variable in the terrestrial system and is highly variable in space and time with typical spatial scales ranging from a few centimeters up to several kilometers. Accurate knowledge of field-scale variability of soil moisture is important for the management of irrigated agriculture. The most commonly used techniques to measure soil moisture at the field scale include point measurements with electromagnetic soil moisture sensors, hydrogeophysical methods, and active and passive microwave remote sensing [1]. However, a gap still exists between local- and regional-scale measurements, which can measure the "true" values of areal soil moisture, an aspect that is very important for both remote sensing validation and hydrological model calibration [2], [3].

A recent method to measure integral soil moisture at the field level or small catchment scale is the cosmic-ray probe (CRP) [4], [5]. CRP counts fast neutrons, produced by secondary cosmic-ray particles, in the soil. There is a negative correlation between near-surface fast neutron counts and soil moisture contents, and this feature enables the use of the CRP to sense soil moisture. The horizontal footprint of the CRP has a radius of about 300 m and is almost independent of soil moisture [6]. In contrast, the measurement in depth is strongly dependent on soil moisture (~76 cm for dry soils (with zero water content) to ~12 cm for saturated soils).

The CRP can accurately measure areal soil moisture at the field level, as demonstrated in several different environmental settings, including a coastal site [7], a desert site [8], an agricultural site [9], and in a low-altitude humid afforested catchment area [10]. A cosmic-ray rover was used to map soil moisture intermediate scale for the calibration and validation of satellite soil moisture data products [11].

This letter demonstrates the applicability of CRP in an agricultural field, which heavily depends on the flooding irrigation. The soil moisture therefore has a high degree of variation in space and time. The validation of Polarimetric L-band Multi-beam Radiometer (PLMR) retrieved soil moisture data shows that the CRP is suitable for remote sensing production validation.

II. Study Area and Data

A. Introduction of the Study Area

The Heihe Watershed Allied Telemetry Experimental Research (HiWATER) Program was a comprehensive ecohydrological experiment carried out in the Heihe River Basin [12]. The first thematic experiment launched was the Multi-Scale Observation Experiment on Evapotranspiration over heterogeneous land surfaces (HiWATER-MUSOEXE), which involved a flux observation matrix in the middle reach of the Heihe River Basin, Gansu, China, during the period between May and September 2012 [13]. This region belongs to the arid desert climate zone, and the average annual precipitation is about 121.5 mm. A typical irrigation district in Zhangye, Daman Irrigation District, was selected to host the experiment. The CRP instrument was located on 100.37225° E, 38.85557° N.

The CRP (named crs_b) was installed on the western side of Daman Superstation [14]. The instrument is equipped with a fast neutron detector, which was placed about 50 cm above the ground, a built-in barometric pressure sensor, and a data logger. The sampling frequency was set to 1 h. Within the footprint area of the CRP, a wireless sensor network (named SoilNET) composed of 19 nodes was deployed to capture the

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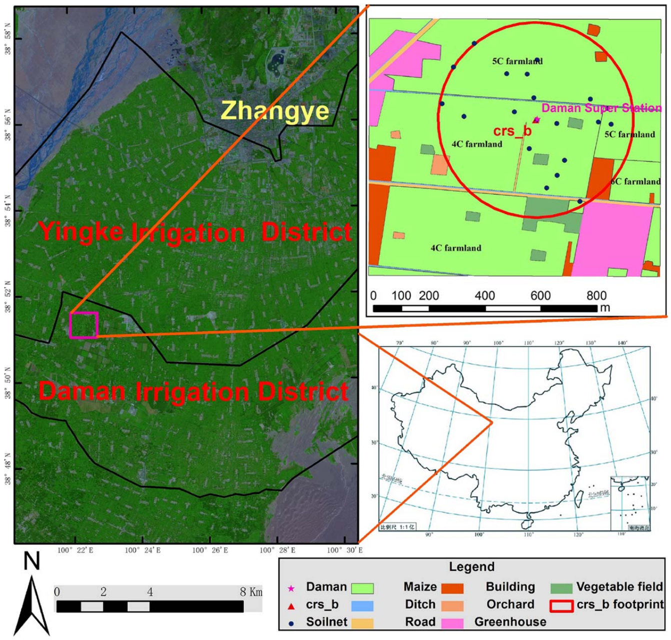

Fig. 1. Layout of the CRP, SoilNET, and the land use of the study area.

heterogeneity of soil moisture and soil temperature [15]–[17]. The layout of the CRP, SoilNET, and the land use of the study area is shown in Fig. 1.

B. Data

The CRP recorded the raw counts of fast thermal neutrons, pressure, relative humidity, and temperature within an hour [18]. Quality control procedures were applied to the raw CRP data before computing the soil moisture according to [5]. The probe began to work on June 1, 2012 [14].

The SoilNET probes measured the soil moisture at depths of 4, 10, 20, and 40 cm with a 10-min interval [19] and then averaged to hourly data to consist with the CRP data.

The Daman Superstation observed a variety of hydrometeorological elements, including precipitation, wind speed, wind direction, air temperature and air humidity gradients (six layers), air pressure, land surface temperature, surface soil heat flux, soil temperature and moisture profiles (eight layers), etc. [20]. Data quality control was applied according to [21] and processed from the original 10-min raw data to hourly data. The soil moisture was measured by CSC616 and calibrated by the gravimetric method.

The PLMR measured soil moisture at 700-m resolution, and data were derived over the study area on six acquisition dates [22]. The PLMR measures both V and H polarizations using a single receiver with polarization switching at incidence angles of $\pm 7^{\circ}$, $\pm 21.5^{\circ}$, and $\pm 38.5^{\circ}$. The accuracy of the PLMR was estimated to be higher than 2 and 3 K in the H and V polarizations, respectively. The method that transfers the raw data from PLMR into soil moisture data was described in greater detail by [23]. During the HiWATER observation campaign, there were six flights over the study area, i.e., June 30, July 3, July 7, July 10, July 26, and August 2, 2012.

III. Calculation of Soil Moisture With Fast Neutrons

A. Footprint and Depth of the CRP

The footprint of the cosmic-ray fast neutron method is defined as the area around the probe, from which 86% of counted neutrons arise. According to the neutron transport code MCNPX (Monte Carlo N-Particle eXtended) simulation results, the diameter of the footprint is about 600 m [6] at sea level, which is consistent with the early neutron transport theory. The footprint is mainly associated with the physical and chemical properties of the atmospheric air and is inversely proportional to the air density, regardless of the surface soil moisture. At high altitude, the air pressure will be lower, and the footprint will be larger than in low altitude areas. For example, the increase of the footprint is approximately 25% between sea level and 3000 m of altitude [5]. The study area is about 1550 m above sea level, and the detection radius can be estimated to about 360 m using the equation as presented in [6].

Depending inversely on soil moisture, the effective depth of measurement, i.e., z, is defined as the layer of soil from which 86% of counted neutrons arise. According to the MCNPX simulated results, the effective depth nonlinearly varies from 12 cm (wet soil, with a water content of 0.40 $\mathrm{m}^3 \cdot \mathrm{m}^{-3}$) to 76 cm (dry soil, with a water content of 0) [5]. A specific formula, as shown in the following equation, is given to calculate this parameter according to MCNPX simulation results [8]:

$$Z = \frac{5.8}{\rho_{\mathrm{bd}} \times \tau + \theta + 0.0829} \tag{1}$$

where ρ_{bd} is the dry bulk density of soil ($\mathrm{g} \cdot \mathrm{cm}^{-3}$), τ is the weight fraction of lattice water in the mineral grains and bound water (very small, ignored in this letter), θ is the volume soil moisture ($\mathrm{m}^3 \cdot \mathrm{m}^{-3}$), and z is effective depth of the soil layer (cm).

B. Corrections

Quality-controlled probe data are corrected to account for temporal changes in air pressure, atmospheric water vapor, and incoming neutron flux [4], [5].

The pressure correction factor f_p is shown as follows:

$$f_p = e^{\frac{(P_0 - P)}{L}} \tag{2}$$

where L is the mass attenuation length for high-energy neutrons (mbar or equivalent in $\mathrm{g} \cdot \mathrm{cm}^{-2}$), which varies progressively between $\sim$128 $\mathrm{g} \cdot \mathrm{cm}^{-2}$ at high latitudes and $\sim$142 $\mathrm{g} \cdot \mathrm{cm}^{-2}$ at the equator [6], P is the air pressure at the specific site, and P_0 is an arbitrary reference pressure, expressed as the long-term average pressure at the specific site.

The atmospheric water vapor correction factor f_{wv} is shown as

$$f_{\mathrm{wv}} = 1 + 0.0054 \times \Delta\rho_{\nu 0} \tag{3}$$

where $\Delta\rho_{\nu 0} = \rho_{\nu 0} - \rho_{\text{ref}}$. $\Delta\rho_{\nu 0}$ is the difference in absolute humidity $(\text{g} \cdot \text{m}^{-3})$ at the time of measurement $(\rho_{\nu 0})$ and at the reference time (ρ_{ref}).

The incoming neutron flux correction factor f_i can be expressed as

$$f_i = \frac{I_m}{I_0} \tag{4}$$

where I_m is the measured neutron intensity, and I_0 is the specified baseline reference intensity. Currently, the neutron intensity at Jungfraujoch, Switzerland, on May 1, 2011, is being used as the reference intensity.

The corrected fast neutron count, i.e., N_{cor}, is obtained by the raw fast neutron count N, as shown in the following equation:

$$N_{\text{cor}} = N \times f_p \times f_{\text{wv}} / f_i. \tag{5}$$

C. Calibration

Since the CRP measures cosmic-ray neutron intensity, the data must be converted to soil moisture using the calibration function, as shown in (6). This conversion requires only one free parameter. Thus

$$\text{SM} = \frac{a_0}{\frac{N_{\text{cor}}}{N_0} - a_1} - a_2 \tag{6}$$

where N_0 is the neutron intensity in the air above dry soil (obtained by calibration), and a_0, a_1, and a_2 are constants that define the shape of the calibration function. For silica soil, computations using the neutron transport code MCNPX provide the following constants: $a_0 = 0.0808$, $a_1 = 0.372$, and $a_2 = 0.115$ [7].

A single representative measurement of average soil moisture content in the footprint will thus be sufficient for calibration. Measured neutron intensity is then compared with the average soil moisture, and the calibration parameter N_0 in (6) is calculated [8].

The SoilNET data of June 23 were used to calibrate the N_0 for (5). For the correction parameters, P_0 was set to 839.65 hPa according to the altitude above sea level (1557 m) of the CRP location, and L was set to 135 $\text{g} \cdot \text{cm}^{-2}$ according to the latitude (N38.85557). ρ_{ref} was set to 0.0863, and I_m was set to 159.15; both were the average value of June 23, 2012. The average soil moisture of 19 SoilNET probes at 4, 10, and 20 cm was used as the compared value. The calibration parameter N_0 in (6) is calculated, and the result, which is 3858 counts/h, is used to calculate the soil moisture using the CRP data. The root-mean-square error (RMSE) of the calibrated soil moisture is 0.0089 $\text{m}^3 \cdot \text{m}^{-3}$.

IV. Results

A. Time Series of Soil Moisture Observed by CRP

The time series of fast neutron derived soil moisture and precipitation during June 1, 2012 and November 13, 2013 are shown in Fig. 2. The precipitation is recorded by the rain gauge installed near the CRP at the Daman Superstation. Averaged soil moisture contents from 2, 4, 10, and 20 cm soil depth, as measured by the Automate Weather Station (AWS) in Daman Superstation, are also shown in Fig. 2.

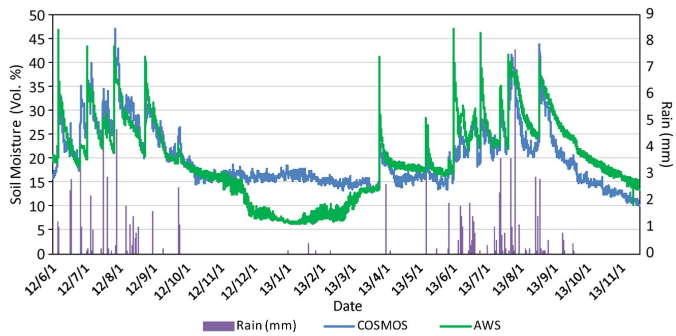

Fig. 2. Time series soil moisture contents by CRP and AWS, Daman Superstation, 2012–2013.

The experimental area has three distinct seasons, i.e., two wet seasons, which are separated by one dry season during winter. The wet soil in the summer is due to heavy flooding irrigation, with four cycles of irrigation during each growing season. Soil moisture remains low (about 15%) in winter, since there is no liquid precipitation and very little snow.

Comparing with the AWS soil moisture, the CRP data have a similar temporal variation with the AWS during the wet seasons. Both methods responded well to precipitation, and both had a fast decrease in soil moisture due to evapotranspiration. However, during the irrigation period, the AWS data are characterized by high intensity and short duration, whereas the CRP data are characterized by relatively lower intensity and longer duration. The reason is that, in the footprint area, the irrigation lasted about 2 days, during which the soil moisture abruptly increased to saturation, and ponding would last for some hours. For the whole CRP footprint, there would not exist a "real" saturation period, since parts of the measurements in footprint take place both before, during and after irrigation.

As regards the winter season (from middle of November to early March), a significant difference is found between soil moisture values observed by CRP and AWS. The soil moisture by CRP shows a very steady trend during the whole season, which means there is almost no change in the soil moisture. This is consistent with the real situation since there is very little evaporation due to low temperatures. Due to snowfall in the beginning and the end of January, the soil moisture by CRP had a slight increase and was followed by a decrease. For the AWS probes, due to frozen water in the soil, the soil moisture abruptly decreased in early December and maintained very small values during most of the season. The reason for this is because the electromagnetic sensors as used for AWS are measuring the soil permittivity, whereas the permittivity of water decreases from 80 to 5 during freezing. Therefore, AWS is not able to properly measure soil moisture in frozen soil. After thawing in early March 2013, the values increased to "normal." In conclusion, the CRP cannot register the frozen and thaw cycle but can measure the snow water, and the AWS probes can monitor the frozen and thaw process but cannot register the snow water until it melts and infiltrates into the soil.

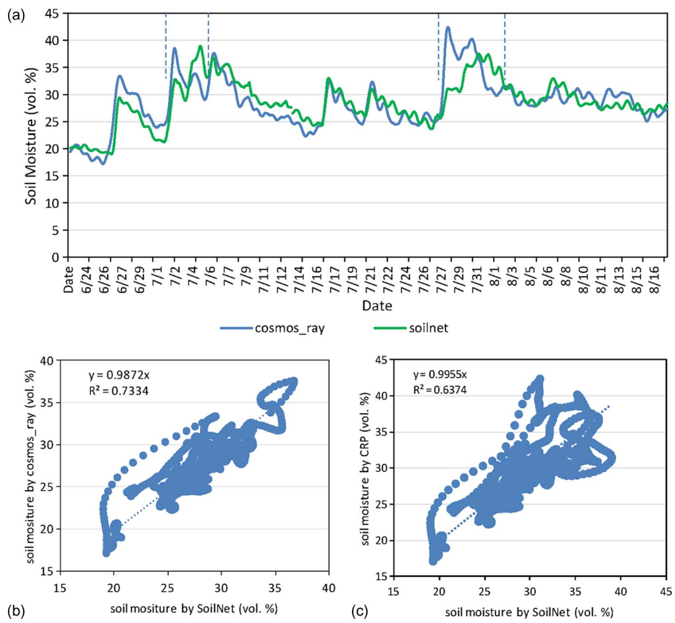

Fig. 3. Comparison of the CRP and SoilNET data. (a) For the entire time period, the dashed lines show the two cycles of irrigation. (b) Scatter plot for the non-irrigation period. (c) Scatter plot for the entire period.

B. Validation of Soil Moisture With SoilNET

Fig. 3 shows the CRP measured soil moisture and the average soil moisture of the 19 SoilNET probes from June 22 to August 18, 2012. The soil moisture data from the CRP were relatively high, and the effective depth was about 15 cm by depth equation [8]. The average from 4, 10, and 20 cm depth soil moisture data from the SoilNET was chosen as the validation data in accordance with the depth of 15 cm (see Fig. 3).

Fig. 3(a) shows that both the CRP and the SoilNET had the same trend during the period of June 22 to August 18. However, there was a significant difference in irrigation time, during which the CRP values were much higher than those of SoilNET. The reason for this is that surface water remained after the irrigation, which results in the overestimation by CRP. Fig. 3(b) shows the comparison of the two measurement methods during the two periods without the irrigation period (July 1 to 15 and July 27 to August 1). Compared with Fig. 3(c) (the coefficient of determination R^2 was 0.64, and RMSE was 0.037 m^3/m^3 for the entire period), the R^2 was significantly higher, reaching 0.73, and RMSE was reduced to 0.0275 m^3/m^3. In conclusion, the experiment shows that, in its footprint, there is a good consistency in the measurements obtained by the CRP, as compared with the SoilNET, and that the CRP method could be used to monitor soil moisture changes in farmland.

C. Comparison of Soil Moisture With PLMR

Validation of soil moisture products from remote sensing is traditionally carried out by averaging point measurements. Given typical levels of observed spatial variability in the fields, this method often fails to achieve the desired objective. The main reason for this is that the method has a significant sampling uncertainty in the footprint scale, since the soil moisture estimates are obtained from sparse ground-based observations. During validation activities based on comparisons between ground observations and PLMR retrievals, this sampling error can be misattributed to retrieval uncertainty and spuriously degrade the perceived accuracy of PLMR soil moisture products.

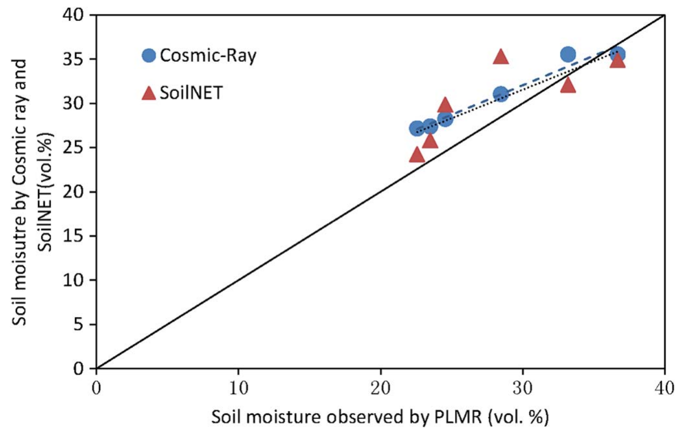

Fig. 4. Comparison of the soil moisture of the CRP, SoilNET, and PLMR.

In order to compare the capability of ground observed areal soil moisture, as obtained by the CRP method, with the averaged point observation in the pixel, the averaged soil moisture of the 19 SoilNET probes was also incorporated in the experiment. At the location of the CRP, each pixel was retrieved from the PLMR soil moisture product data. Since the footprint of the CRP has a radius of 350 m, the pixel of the PLMR is almost the identical.

Fig. 4 shows the relationship between the soil moisture observed by CRP, the averaged SoilNET probes, and the PLMR retrieved data. It is clearly seen that, with an R^2 value of 0.96, the soil moisture data by the CRP have a much better relationship with the PLMR retrieved soil moisture. The averaged SoilNET has almost the same slope of the trend line. However, the R^2 value is only about 0.64 and has a much more scattered distribution from the line. This means that the CRP could be used as a tool for validation of remote sensing products and that the CRP has a much better accuracy than the averaged points measurement, at least when the points are not very densely distributed.

The average soil moisture of the PLMR pixel is 28.17%, which is slightly less than both the CRP and the SoilNET probe, which are 30.81% and 30.36%, respectively. The main reason for this is because the PLMR observes about up to 5 cm soil depth only, whereas the CRP can measure the soil moisture up to about 15 cm depth according to the soil moisture value in these days. Fig. 4 also shows that the CRP has a similar value, as compared with the PLMR when the soil moisture is larger (>30%), and larger than the PLMR when the soil moisture is small. This could be a result of a situation when the soil is dry, and the CRP therefore can measure to a deeper soil depth.

V. Conclusion

The newly developed CRP measuring method for area-average soil moisture, at the hectometer horizontal scale, was implemented in the 2012 observation campaign of HiWATER in irrigated land in the Zhangye Oasis in Gansu. Data analysis shows that the CRP is able to measure the real areal soil moisture. As compared with the traditional point observation methods, it could measure the real water content in the soil and snow but cannot detect the water during frozen and thaw processes. During irrigation, the presence of surface water can lead to overestimation of the soil moisture. In the non-irrigated period, the CRP has a very strong correlation with the averaged soil moisture of 19 SoilNET probes in its footprint, whose R^2 is 0.73 and RMSE is 0.0275. In comparison with the PLMR, which has a pixel resolution of 700 m, the CRP has much better results than the averaged SoilNET, with a coefficient of determination of 0.96 and 0.64, respectively. Although the CRP still has some limitations, for example, the presence in the footprint of hydrogen, other than that in soil water (in hydrous minerals or in vegetation and soil organic matter [5], [24]), it can be concluded that it is a robust method, which can be used to get the "true" value of soil moisture at field level for remote sensing validation.

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