SOIL MOISTURE ESTIMATION USING GNSS REFLECTOMETRY IN CAMBODIA

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Abstract

Soil moisture content is a fundamental variable for understanding Earth surface hydrological processes, as well as for monitoring drought cycles, both locally and globally. In this work, we present the process of converting GNSS reflectometry data acquired by the CyGNSS satellite constellation into surface soil moisture content (SMC). For this purpose, bare soil roughness and vegetation optical depth data, supplied by SMAP Level 2 products, are crucial. The chosen area is a region in Southeast Asia, and in order to evaluate changes in the SSMC variable, the study was conducted over two temporal intervals spread throughout the year 2024. The results achieved show good agreement with SMC estimated from the SMAP system, as well as from other international environmental services.

Key words: *GNSS-R, CYGNSS, Remote Sensing, Soil Moisture Content estimation.*

INTRODUCTION

Soil moisture is a key factor influencing various biological and ecological processes. Its proper management is essential for sustainable agriculture and environmental health. This variable impact plant growth, the regulation of processes like photosynthesis and organic matter decomposition, among others. Furthermore, it plays an important role in preventing erosion, water filtration, and groundwater protection. Likewise, soil moisture content depends on other external factors, primarily meteorological conditions and climate change *(Entekhabi et al., 2010)*.

The implications of soil moisture can have diverse impacts depending on the observation scale, i.e., local, regional, or global. A wide range of methods and sensors are available for its measurement, as well as remote sensing *(Zeiger et al., 2022)*, either from drones or via satellite technology. In any case, choosing the most appropriate measurement method is always required, as the most useful procedures for one scale are not necessarily the most correct for others. For regional and/or global scales, space-based remote sensing is the most convenient, as it can provide observations for extensive areas of the Earth's surface.

Instruments used to measure Soil Moisture Content *(SMC)* from satellite Earth observation missions can be classified by their technology or by detection principle. The first divides into two types of technologies: optical and microwave, while the second distinguishes between passive and active systems. This study will use an active system with microwave technology, given its ability to operate with cloud cover and in the absence of natural illumination *(Yang et al., 2023)*. Among the conventional systems of this type are monostatic Earth observation radar antennas. These systems have shown their sensitivity to the physical properties of the observed surface, among which soil moisture stands out.

However, for a little over a decade, within this field, the capabilities of new systems based on Signal of Opportunity *(SoOP)* are being tested. This new generation of systems relies on capturing, with a microwave antenna, the signal reflected by the Earth's surface that originates from GNSS system constellations, hence their name: GNSS Reflectometry or GNSS-R *(Kurum et al., 2017)*. These systems operate as bistatic radars, and both this measurement method and the various instruments that have been developed since the beginning of this century are demonstrating their operability and capacity to extract essential environmental variables, including SMC.

Among all of them, NASA's CyGNSS *(Cyclone Global Navigation Satellite System)* mission, operational since 2018, stands out. Since then, it has provided an immense amount of measurements across the entire Earth's surface, from which it is possible to globally extract SMC. The objective of this work is to demonstrate the capabilities of this technology to provide an efficient method for calculating SMC and thus estimate SMC in an extensive area of Southeast Asia.

MATERIALS AND METHODS

The area covered by this study spans Southeast Asia and includes the country of Cambodia, as well as other regions in neighboring countries. This represents an area exceeding 181,035 km². This zone was observed by NASA's CyGNSS mission throughout 2024. The data used from this mission corresponds to the CYGNSS Level 1 *(L1 V3.2)* science data record dataset (https://podaac.jpl.nasa.gov/dataset/CYGNSS_L1_V3.2), which contains geo-located Delay Doppler Maps *(DDM)* calibrated into Power Received with the DDM instrument aboard the CyGNSS satellite constellation. Additionally, surface roughness *(BSR)* and Vegetation Optical Depth *(VOD)* data acquired by NASA's SMAP *(Soil Moisture Active Passive)* mission (https://smap.jpl.nasa.gov/), operational since 2015, were used. This data is necessary for correcting CyGNSS reflectivities. In this study, the SMAP data also covers the period from January 1, 2024, to December 31 of the same year. The SMC (Soil Moisture Content) variable obtained from this mission was also employed for comparison with the SMC extracted from CyGNSS reflectivities.Thus, the procedure to obtain soil moisture content from the power values received by the antennas of the different satellites in the CyGNSS constellation begins by calculating the reflectivities of the specular points using the bistatic radar equation *(eq.1)* adapted for a GNSS_R system for coherent specular points *(Yang et al., 2023)*:

$$\Gamma_{rl} = \frac{(4\pi)^2 (P_{DDM})(R_{st} + R_{sr})^2}{\lambda^2 G_r G_t P_t} \quad (1)$$

P_t is the transmitted power *(Watts)* from the GNSS antennas, $G_r$and G_t are the receiver and transmitter antenna gains *(Watts)*, R_{st} and R_{sr} are the respective ranges to the specular points from the transmitter and receiver antennas *(m)*, P_{DDM} is the Delay Doppler Map Power *(Watts)* or the considered received power, λ the system frequency *(m)*, and Γ_{rl} the computed surface reflectivity in circular polarization. It is important to point out that in this work, the coherent component of the received power is considered. To reduce these values to the ground surface *(Dong et al., 2023)*, these reflectivities must be corrected for the effects caused by surface roughness *(σ)* and vegetation optical depth *(VOD)*, designated in this instance by the letter τ *(eq. 2a and eq. 2b)*. In all these equations, the subscript "*lr*" designates the "left-right" circular polarization state and θ_i refers to observed the incidence angle .

$$|R_{lr}(\theta_i)|^2 = \frac{\Gamma_{lr}}{exp^{-(2k\sigma cos\theta_i)^2}\, exp^{-(\tau/cos\theta_i)^2}} \quad (2)$$

As indicated later, the BSR and VOD data come from SMAP products. Efforts have been made to ensure all data and values are on the same temporal scale. Once the corrected reflectivities are calculated, the next process involves obtaining the real component part of permittivity *(ε_r)*, for which the reflectivity in circular polarization must be converted to linear polarization. The relationship between these states is established by equality *(eq. 3)*:

$$R_{lr} = R_{rl} = \frac{1}{2}(R_{vv} - R_{hh}) \quad (3)$$

Now, the sub-indices "*hh*" and "*vv*" stand for the linear polarization states. *Rvv* and *Rhh* represent by the two Fresnel coefficients from where the real component part for the permittivity can be derived. This operation can be performed by mathematical numerical analysis *(Brent, 1973)*. Finally, the soil moisture content is converted from the derived permitivities using the Hallikainen formula *(Hallikainen, 2014)*, equation 4:

$$M_v = -5.3\times10^{-2} + 2.92\times10^{-2}\times\varepsilon_{r\_soil} - 5.5\times10^{-4}\times\varepsilon_{r\_soil}^2 + 4.3\times10^{-6}\times\varepsilon_{r\_soil}^3 \quad (4)$$

RESULTS AND DISCUSSION

Fig. 1a shows corrected reflectivities of the study area which is based on equations *(1)* and *(2)*. Major contributor to the correction of reflectivity in equation *(2)* is Vegetation optical depth that was extracted from the SMAP datasets, it is shown in the Fig. 1b. Particularly, these data are derived from the June 2024 products.

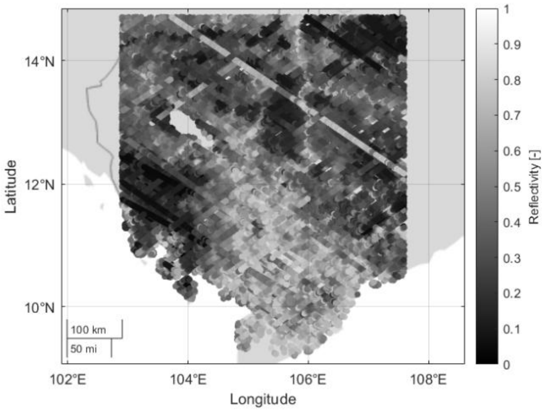

Fig. 1a CyGNSS Reflectivity 2024/06/01-15

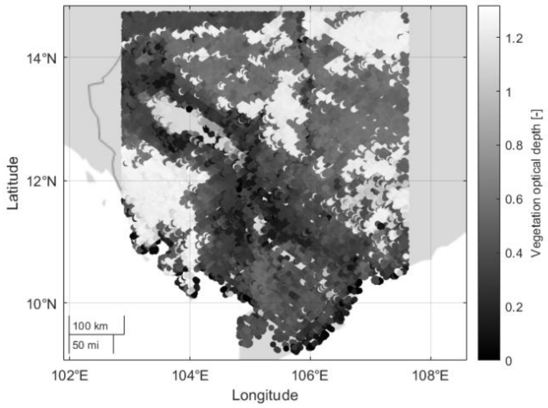

Fig. 1b SMAP VOD 2024/06/01-15

The effect of vegetation is visible in Fig. 2a and Fig. 3a, particularly around the lake Tonlé Sap and in the east part of Cambodia where the value of vegetation optical depth in Fig. 1b is above 1. The dense vegetation lowers the amount of signal, that gets reflected which causes loss of information about soil moisture content.

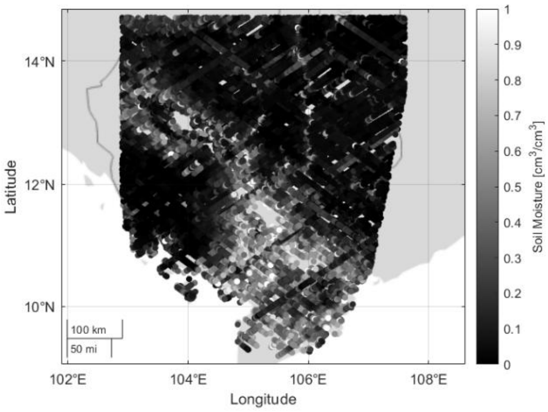

Fig. 2a CyGNSS SMC 2024/01/01-15

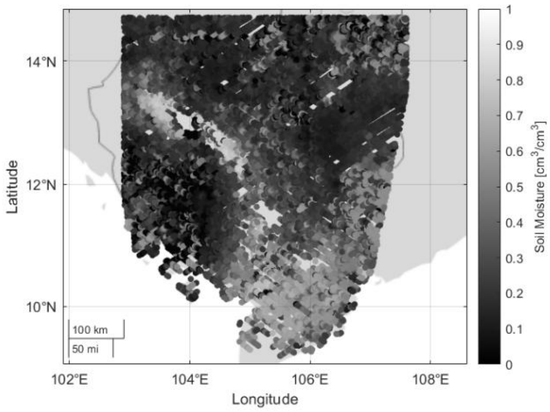

Fig. 2b SMAP SMC 2024/01/01-15

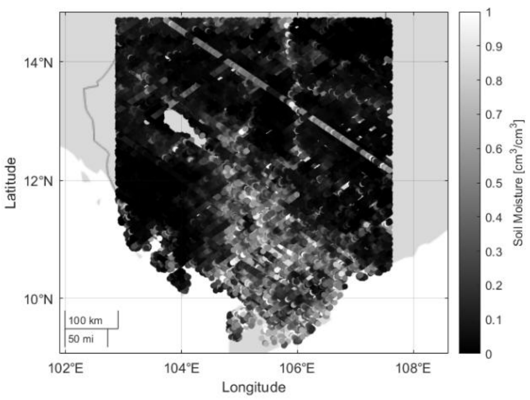

Fig. 3a CyGNSS SMC 2024/06/01-15

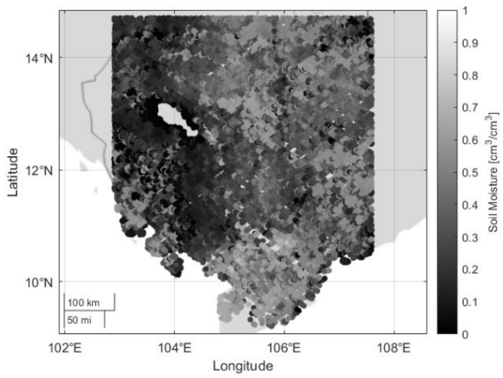

Fig. 3b SMAP SMC 24/06/01-15

The Fig. 2a and Fig 3a show change in soil moisture, computed from CyGNSS, between January 2024 and June 2024, respectively. The change agrees with the change in soil moisture extracted from the

SMAP dataset, between the same dates, which is shown in the Fig. 2b and Fig. 3b. It is especially visible in the area around the lake Tonlé Sap, where the value of vegetation optical depth is below 1. This effect of vegetation on signal quality is corroborated by other research. For instance, Zeiger et al. *(2022)* also found that dense canopies can cause strong attenuation of the L-band signal, leading to an underestimation of floods. Their work further confirmed that flooded areas are detected less accurately under forests than under herbaceous cover.

CONCLUSIONS

This work demonstrates the capabilities of GNSS reflectometry data for estimating soil moisture content *(SMC)* values. To achieve this, data from the CyGNSS mission serve as a reliable source of information for obtaining SMC values. However, one of the limitations of the CyGNSS system is its inability to work with dual polarizations, which hinders the direct estimation of SMC. Nevertheless, numerical analysis methods have been shown to overcome this problem.

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ISBN 978-80-213-3541-7