

Monitoring a Short-Term Dry-to-Wet Soil-Moisture Transition Using GPS Multipath in Tropical Environment

Arizal Bawasir^{1*}, Adistina Lailia Fajar Dewi², Putri Aditya Padma Pertiwi³, Dimar Fatwa Laksono⁴, Aldy Lois Pranata Sinurat⁵, Syachrul Arief⁶

¹ Geomatics Engineering Department, Universitas Pembangunan Nasional “Veteran” Yogyakarta, Indonesia

² Soil Science Department, Universitas Pembangunan Nasional “Veteran” Yogyakarta, Indonesia

³ Geomatics Engineering Department, Universitas Pembangunan Nasional “Veteran” Yogyakarta, Indonesia

⁴ Geomatics Engineering Department, Universitas Pembangunan Nasional “Veteran” Yogyakarta, Indonesia

⁵ Geomatics Engineering Department, Universitas Pembangunan Nasional “Veteran” Yogyakarta, Indonesia

⁶ Geospatial Information Agency of Indonesia (Badan Informasi Geospasial), Indonesia

Received : July 30, 2026

Revised : August 1, 2026

Accepted : August 3, 2026

Online : October 7, 2026

Abstract

Continuous local observations of surface soil moisture remain limited in humid tropical regions, where optical monitoring is frequently interrupted by cloud cover. This study evaluates whether an operational Continuously Operating Reference Station can resolve a short dry-to-wet transition using Global Navigation Satellite System Interferometric Reflectometry. GPS L2C signal-to-noise ratio observations from the CPLU station in North Padang Lawas, North Sumatra, were processed at elevation angles of 10°–25° and azimuths of 0°–180°. Direct-signal trends were removed, and accepted multipath arcs were screened using Lomb–Scargle peak criteria. Track-specific phase changes were transformed into a consistently scaled daily relative volumetric water content series. A stable dry interval identified from SMAP supplied the lower relative baseline, and September 2025 was retained as the focused transition month. GNSS-IR-derived relative volumetric water content (VWC-GNSSIR) increased from 0.070 m³/m³ at the beginning of September to 0.290 m³/m³ near month-end. The monthly mean was 0.179 m³/m³, and local rainfall totaled 135.6 mm across 17 rainy days. Across six cloud-free Sentinel-2 observations from the broader season, the original NDVI showed a strong descriptive association with VWC-GNSSIR ($r = 0.871$), whereas a three-month moving composite produced a weaker relationship (r approximately 0.390). The results demonstrate that CORS-based GNSS-IR can capture short-term tropical soil-moisture dynamics that are substantially smoothed in temporally aggregated optical products.

Keywords GNSS-IR, CORS, Soil-Moisture Dynamics, Sentinel-2 NDVI, Tropical Hydrology

INTRODUCTION

Surface soil moisture controls how rainfall partitions into infiltration, runoff, evaporation, and plant water uptake. It also regulates land-atmosphere exchanges and influences drought and flood development. Continuous observations are therefore important in humid tropical regions, where short drying intervals and recurrent rainfall can produce rapid surface changes (Seneviratne et al., 2010; Ochsner et al., 2013). For GNSS-IR, persistent vegetation can modify reflected-signal amplitude and phase and therefore requires careful track-wise processing (Chew et al., 2016; Small et al., 2016). Recurrent rainfall can also shorten stable dry periods and produce surface changes

Copyright Holder:

© Arizal, Adistina, Putri, Dimar, Aldy, & Syachrul. (2026)

Corresponding author's email: arizalbawasir@upnyk.ac.id

This Article is Licensed Under:



between successive satellite arcs.

Existing observation systems differ in scale and continuity. In situ probes measure a small soil volume, regional microwave products represent much larger grid cells, and optical imagery is often limited by tropical cloud cover. GNSS Interferometric Reflectometry (GNSS-IR) offers an intermediate footprint by using ground-reflected signals already recorded at geodetic stations. Recent studies have demonstrated soil-moisture retrieval from operational GNSS stations in tropical Tanzania and Brazil ([Mkoy et al., 2024](#); [Euriques et al., 2025](#)). However, evidence remains limited for humid equatorial Indonesia and for short dry-to-wet transitions resolved at an operational CORS. This leaves an important gap in understanding whether existing CORS can preserve short-lived surface-moisture changes when optical observations are sparse.

At low elevation angles, direct and reflected GNSS signals interfere, creating quasi-periodic oscillations in the signal-to-noise ratio (SNR). Changes in near-surface water content modify soil dielectric properties and shift the phase of these oscillations ([Larson et al., 2010](#); [Zavorotny et al., 2010](#); [Chew et al., 2014](#)). Continuously Operating Reference Stations (CORS) can therefore support environmental monitoring without dedicated soil-moisture hardware ([Larson et al., 2008b](#)).

Accordingly, this study examines September 2025 at the CPLU CORS in North Sumatra. The month marks the first sustained recovery after the low-moisture conditions of July and August and includes a pronounced late-month wetting sequence. The objectives are to describe the essential GPS L2C processing, characterize the monthly evolution of GNSS-IR-derived relative volumetric water content (VWC-GNSSIR), and compare its temporal behavior with the original and three-month composite Sentinel-2 NDVI. SMAP is used only to identify a stable dry-period baseline. Theoretically, the study evaluates whether track-wise interferometric phase retains coherent short-term moisture dynamics under humid tropical conditions. Practically, it evaluates reusing existing CORS infrastructure as a continuous local complement to rainfall and satellite observations where dedicated soil-moisture sensors are sparse.

LITERATURE REVIEW

GNSS-IR Soil-Moisture Sensing

[Larson et al. \(2008a\)](#) first demonstrated GPS multipath as a soil-moisture observable. Later algorithms established interferometric phase as the principal retrieval variable and introduced procedures for bare and vegetated surfaces ([Chew et al., 2014](#); [Chew et al., 2016](#)). Each satellite track's footprint depends on antenna height, elevation, and azimuth. Environmental screening and track-wise processing are therefore required before combining several arcs into a robust daily estimate ([Small et al., 2016](#)).

Operational CORS and Optical Support

Open-source software has improved the reproducibility of GNSS-IR processing at operational CORS ([Larson, 2024](#)). Recent active-station studies in tropical Tanzania and Brazil show that screened CORS observations can recover soil-moisture dynamics when station geometry and track selection are suitable ([Mkoy et al., 2024](#); [Euriques et al., 2025](#)). Sentinel-2 adds local spatial detail, although NDVI represents vegetation greenness rather than direct soil water content. Cloud-free observations can support broad temporal interpretation, while moving composites increase availability at the cost of smoothing short-lived changes.

RESEARCH METHOD

Study Site and Data

CPLU is located in the Aek Godang meteorological compound in North Padang Lawas Regency, North Sumatra, at approximately 1°23'55.29" N and 99°25'51.55" E. The antenna phase

center is about 3.3 m above ground. Site photographs and first Fresnel-zone inspection identified an open reflection sector between azimuths 0° and 180°, as shown in Figure 1.

The primary data were 30 s RINEX observations from the Ina-CORS service. The complete processing record extended from 18 March to 31 December 2025, while only September was retained for the principal short-term result. GPS L2C SNR was used because it was consistently available. Daily rainfall came from the BMKG gauge approximately 30 m from CPLU. Sentinel-2 Surface Reflectance Harmonized imagery was obtained through Google Earth Engine and screened for valid pixels around the station (Gorelick et al., 2017).

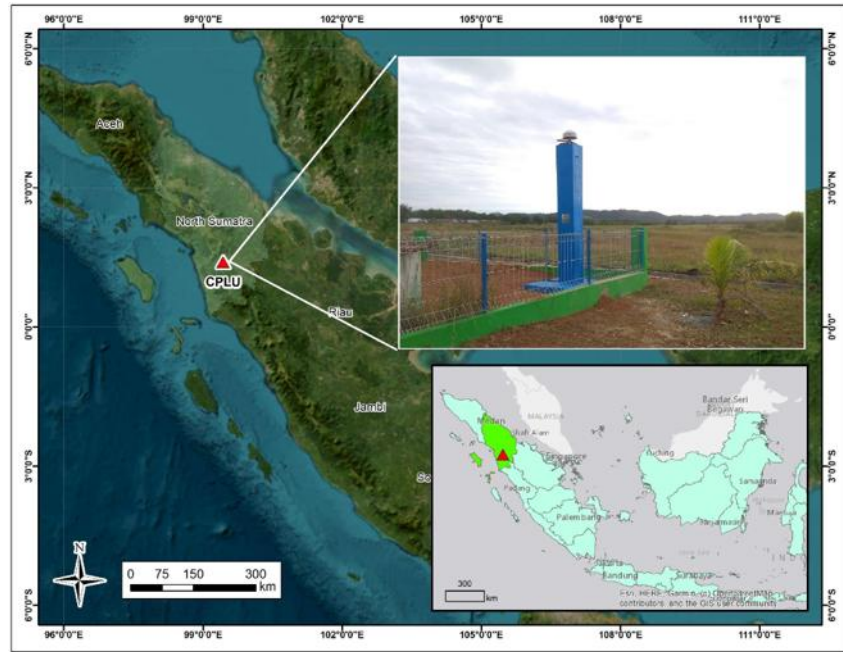


Figure 1. Location of the CPLU CORS in North Sumatra and the open surface surrounding the monument

GNSS-IR Processing

Processing used the open-source gnsirefl package (Larson, 2024). Rising and setting GPS L2C arcs were restricted to elevations of 10°–25° and the selected 0°–180° azimuth sector. Reflector height was identified from the dominant Lomb–Scargle periodogram peak. Accepted arcs required a peak amplitude of at least 8 V/V and a peak-to-noise ratio of at least 2.7. Recorded SNR in dB-Hz was first converted to a linear voltage ratio.

$$\text{SNR}_{\text{lin}} = 10^{(\text{SNR}_{\text{dB-Hz}} / 20)} \quad (1)$$

A low-order polynomial $P(e)$ represented the slowly varying direct-signal component at elevation e . Subtracting this trend retained the multipath-dominated residual.

$$\text{SNR}_{\text{res}}(e) = \text{SNR}_{\text{lin}}(e) - P(e) \quad (2)$$

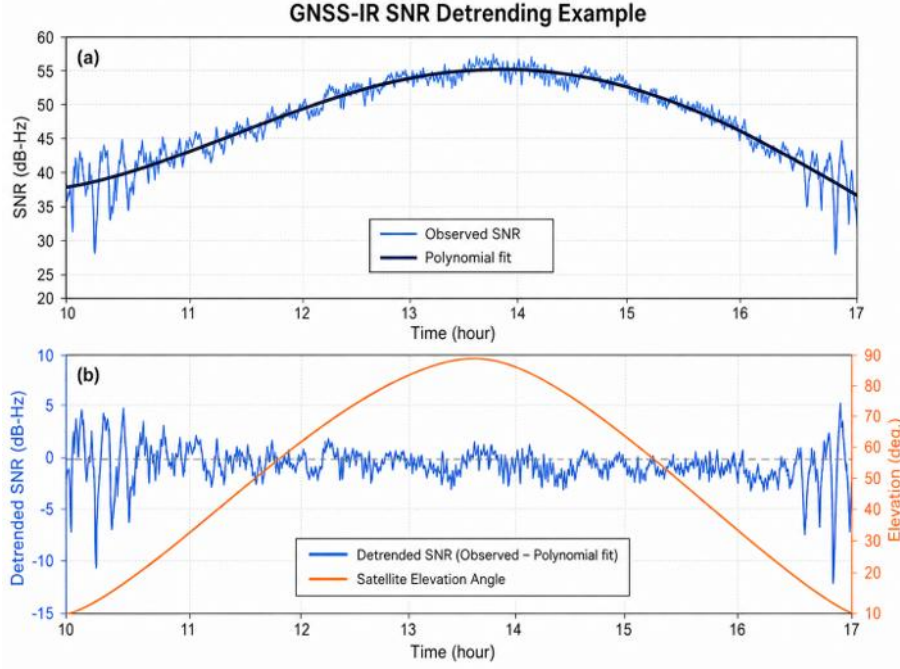


Figure 2(a). Polynomial detrending of observed GPS L2C SNR and the residual retained for phase estimation

The residual oscillation was analyzed independently for each accepted satellite track. Its interferometric phase supplied the soil-moisture observable. Persistent offsets were removed within each PRN, and the normalized phase index was mapped to a fixed VWC reporting interval.

$$VWC_GNSSIR,t = VWC_{min} + \varphi_{in} d_{ex,t} (VWC_{max} - VWC_{min}) \quad (3)$$

In Equation (3), VWC_{min} and VWC_{max} are the adopted reporting limits, and the phase index expresses the relative position of phase between the observed limits for the same PRN. Daily VWC-GNSSIR was the median of five to seven accepted tracks from PRNs 8, 15, 16, 20, 21, 26, and 32.

Transition Window, Baseline, and Optical Analysis

The full record was retained during processing so that track-specific phase limits were defined consistently. July and August formed the most persistent low-moisture interval. September was selected because its mean VWC-GNSSIR increased to $0.179 \text{ m}^3/\text{m}^3$ from $0.086 \text{ m}^3/\text{m}^3$ in August and because a clear wetting sequence occurred near month-end.

No in situ sensor was available in the CPLU reflection area. The SMAP Enhanced Level-3 record for the grid cell containing CPLU was used only to locate the regional interval in which SMAP and GNSS-IR both remained low. This interval supplied the lower relative baseline. SMAP was not treated as a point-scale substitute because its 9 km grid integrates a much broader surface (O'Neill et al., 2023). Sentinel-2 red-band and near-infrared reflectance were used to calculate NDVI for valid pixels around CPLU.

$$NDVI = (NIR - Red) / (NIR + Red) \quad (4)$$

Two optical series were evaluated. The first retained original cloud-free observations on their exact acquisition dates. The second used a three-month moving composite. Six valid original dates occurred between June and October, but none fell within September. The one-month transition and the optical association were therefore interpreted as complementary analyses. Pearson correlation described the linear association between paired VWC-GNSSIR and NDVI observations. Because the original optical sample was small, the coefficients were interpreted descriptively rather than as calibration statistics.

FINDINGS AND DISCUSSION

Evidence from SNR Processing

Figure 2(b) presents representative GPS L2C oscillations for PRNs 16 and 21 under relatively dry and wet conditions.

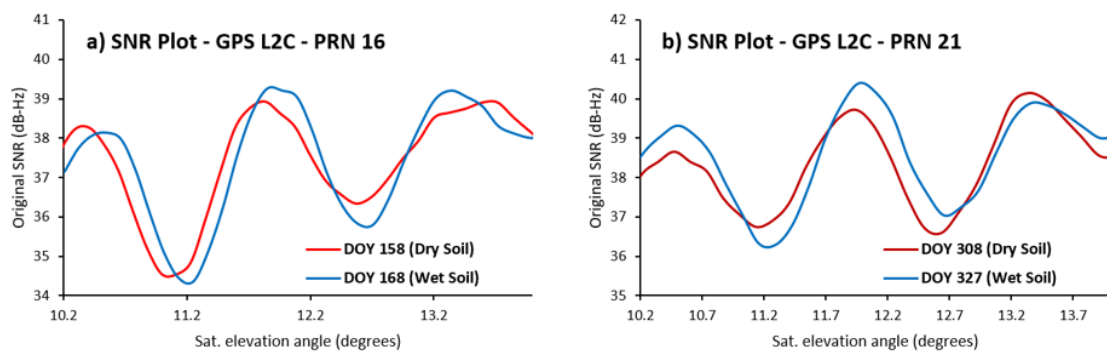


Figure 2(b). Representative GPS L2C oscillations for PRN 16 and 21 under relatively dry and wet conditions

The peak and trough positions shift between the two moisture conditions for both PRNs. Because the tracks sample different reflection sectors, their consistent directional response supports using phase change as the common observable before daily aggregation. Figure 2(a) establishes that this phase information is retained only after the broad direct-signal trend has been removed.

September 2025 Dry-to-Wet Transition

September began at $0.070 \text{ m}^3/\text{m}^3$ and rose to $0.180 \text{ m}^3/\text{m}^3$ on 4 September after early-month rainfall. Values then fluctuated mainly between 0.15 and $0.21 \text{ m}^3/\text{m}^3$, indicating repeated wetting and drying rather than an immediate shift to persistently wet conditions.

The strongest transition followed late-month rainfall. Rainfall totals of 23.8 and 56.8 mm were recorded on 27 and 28 September. VWC-GNSSIR increased from $0.206 \text{ m}^3/\text{m}^3$ on 26 September to $0.251 \text{ m}^3/\text{m}^3$ on 27 September and $0.284 \text{ m}^3/\text{m}^3$ on 28 September. It reached $0.290 \text{ m}^3/\text{m}^3$ on 29 September and remained elevated at $0.261 \text{ m}^3/\text{m}^3$ on the final day.

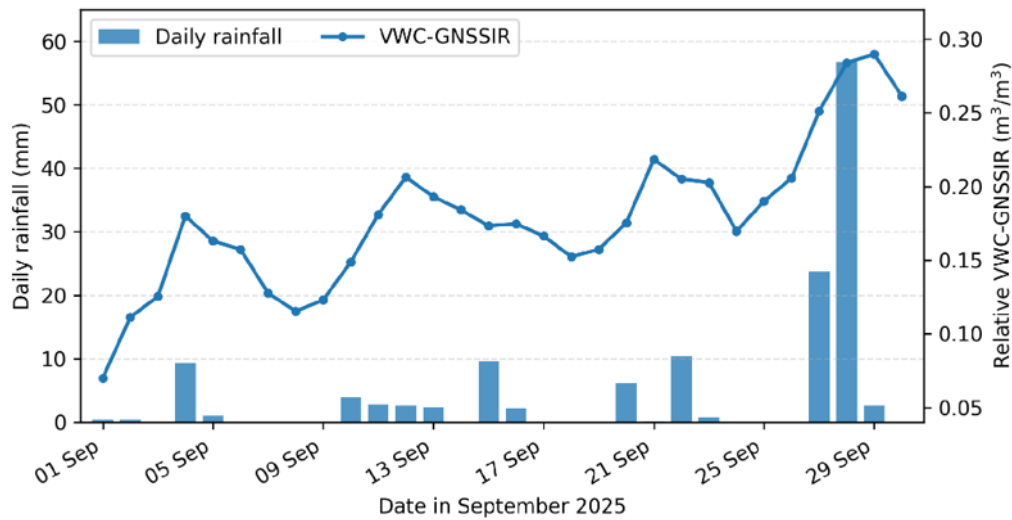


Figure 3. Daily relative VWC-GNSSIR and rainfall at CPLU during September 2025

Table 1. Summary of the September 2025 CPLU transition window.

Daily n	Minimum VWC	Maximum VWC	Mean VWC	Median VWC	Total rainfall	Rainy days
30	0.070 m ³ /m ³	0.290 m ³ /m ³	0.179 m ³ /m ³	0.175 m ³ /m ³	135.6 mm	17

The monthly mean of 0.179 m³/m³ was more than twice the August mean. Rainfall totaled 135.6 mm across 17 rainy days, so the final two storms did not control the monthly recovery. Continuous daily sampling also captured temporary declines between events that longer or irregular revisit intervals could miss.

Association with Original and Composite Sentinel-2 NDVI

Figure 4 compares VWC-GNSSIR with original and composite NDVI. Original cloud-free observations mainly sampled the mid-year low-moisture interval and one recovery observation in late October. The moving composite filled part of the temporal record but converted the observations into a smoother sequence.

The six original observations produced $R^2 = 0.7589$ and a positive slope, corresponding to Pearson $r = 0.871$. Lower NDVI values accompanied the dry interval, whereas the late-October observation was associated with higher VWC-GNSSIR. The result indicates a strong descriptive association within the available sample, but NDVI remains an indicator of vegetation condition rather than direct soil water.

The three-month composite produced $R^2 = 0.1523$ and r approximately 0.390. Temporal averaging combines conditions before and after a GNSS-IR date, which attenuates short wetting and drying changes. The composite improves continuity, while the original product preserves greater temporal correspondence with the daily GNSS-IR series.

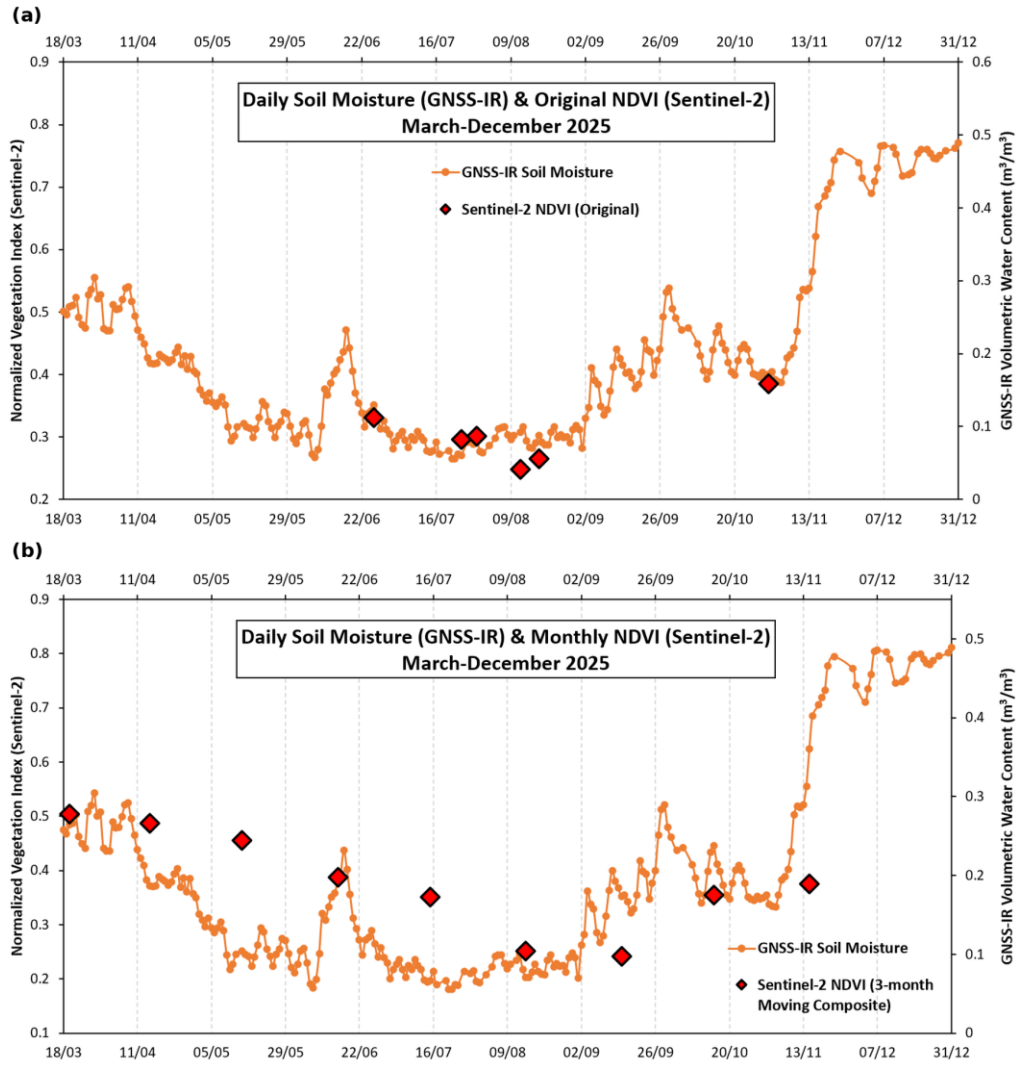


Figure 4. VWC-GNSSIR with Sentinel-2 NDVI. (a) Original cloud-free acquisitions. (b) Three-month moving composite

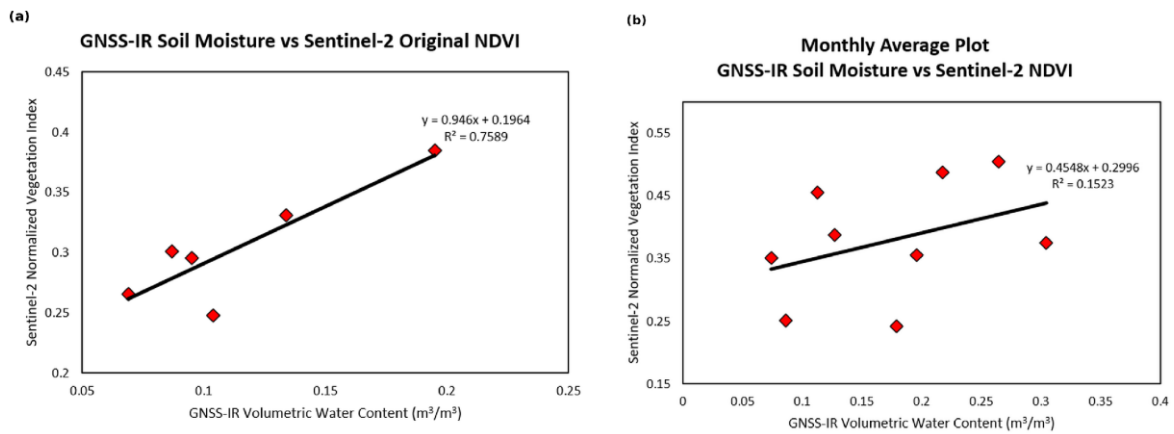


Figure 5. Relationships between relative VWC-GNSSIR and Sentinel-2 NDVI. (a) Original cloud-free observations. (b) Three-month moving composite

Implications

The September case demonstrates that an operational CORS can describe a transition from low to higher surface moisture without a separate probe. GNSS-IR samples a ground area larger than a point sensor but much smaller than a regional microwave grid. When a station has an open and stable reflection sector, GNSS-IR provides local hydrometeorological information with spatial support between point measurements and regional products. This makes existing CORS infrastructure potentially useful for complementing rainfall and satellite monitoring without installing a dedicated soil-moisture sensor at every station.

CONCLUSIONS

GPS L2C observations from CPLUS produced a coherent daily VWC-GNSSIR record for September 2025. The series increased from $0.070 \text{ m}^3/\text{m}^3$ at the beginning of the month to $0.290 \text{ m}^3/\text{m}^3$ near month-end. The most pronounced increase followed consecutive rainfall on 27 and 28 September. The monthly mean was $0.179 \text{ m}^3/\text{m}^3$, while rainfall totaled 135.6 mm across 17 rainy days.

Original cloud-free NDVI showed a stronger descriptive association with VWC-GNSSIR than the three-month composite, supporting the conclusion that temporal aggregation can suppress short-lived wetting and drying signals. Taken together, the results fulfill the study objective by showing that GPS L2C multipath from a suitably located CORS can track a one-month dry-to-wet surface-moisture transition in a humid tropical environment. Operationally, the approach can complement rainfall gauges and satellite products by reusing continuous geodetic infrastructure. Further work should include in situ calibration, vegetation measurements, longer seasonal records, and replication at additional Indonesian stations with open reflection sectors

LIMITATIONS & FURTHER RESEARCH

This case study has three main boundaries. First, the focused analysis covers only September 2025, so it does not represent the full seasonal response. Second, no co-located in situ sensor was available in the CPLUS reflection area, and the reported VWC scale is therefore interpreted through temporal dynamics rather than site-specific volumetric calibration. Third, persistent cloud cover limited the original Sentinel-2 comparison to six valid observations across the broader season, while NDVI represents vegetation condition rather than direct soil water. Future experiments should extend the analysis across wet and dry seasons and add local soil-moisture and vegetation measurements within the dominant Fresnel zones.

Acknowledgment

The authors gratefully acknowledge financial support from the Internal Research Grant of Universitas Pembangunan Nasional “Veteran” Yogyakarta under Grant Contract No. 190/UN62.21/PG.00.00/2026. The authors also acknowledge the Geospatial Information Agency (Badan Informasi Geospasial – BIG) for Ina-CORS observations and Meteorological-Climatological-and-Geophysical Agency (*Badan Meteorologi Klimatologi dan Geofisika* (BMKG)) for local rainfall records.

Data Availability

CPLUS RINEX observations are available through the Ina-CORS and Spatial Reference System of Indonesia services under the provider's access conditions (<https://srgi.big.go.id/map/jkg-active>). BMKG rainfall records are available through Data Online BMKG (<https://dataonline.bmkg.go.id/>). SMAP and Sentinel-2 collections are accessible through Google Earth Engine. Derived September data and processing settings may be requested from the

corresponding author.

REFERENCES

- Chew, C. C., Small, E. E., Larson, K. M., & Zavorotny, V. U. (2014). Effects of near-surface soil moisture on GPS SNR data: Development of a retrieval algorithm for soil moisture. *IEEE Transactions on Geoscience and Remote Sensing*, 52(1), 537-543. <https://doi.org/10.1109/TGRS.2013.2242332>
- Chew, C. C., Small, E. E., & Larson, K. M. (2016). An algorithm for soil moisture estimation using GPS-interferometric reflectometry for bare and vegetated soil. *GPS Solutions*, 20(3), 525-537. <https://doi.org/10.1007/s10291-015-0462-4>
- Euriques, J. F., Veiga, L. A. K., Machado, W. C., Krueger, C. P., & Geremia-Nievinski, F. (2025). Soil moisture estimation by GNSS-IR from active stations: Case study – RBMC/IBGE, UFPR Station. *Anuário do Instituto de Geociências*, 48, 65911. https://doi.org/10.11137/1982-3908_2025_48_65911
- Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, 202, 18-27. <https://doi.org/10.1016/j.rse.2017.06.031>
- Larson, K. M., Small, E. E., Gutmann, E. D., Bilich, A. L., Axelrad, P., & Braun, J. J. (2008a). Using GPS multipath to measure soil moisture fluctuations: Initial results. *GPS Solutions*, 12, 173-177. <https://doi.org/10.1007/s10291-007-0076-6>
- Larson, K. M., Small, E. E., Gutmann, E. D., Bilich, A. L., Braun, J. J., & Zavorotny, V. U. (2008b). Use of GPS receivers as a soil moisture network for water cycle studies. *Geophysical Research Letters*, 35, L24405. <https://doi.org/10.1029/2008GL036013>
- Larson, K. M., Braun, J. J., Small, E. E., Zavorotny, V. U., Gutmann, E. D., & Bilich, A. L. (2010). GPS multipath and its relation to near-surface soil moisture content. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 3(1), 91-99. <https://doi.org/10.1109/JSTARS.2009.2033612>
- Larson, K. M. (2024). Gnsirefl: An open source software package in Python for GNSS interferometric reflectometry applications. *GPS Solutions*, 28, 165. <https://doi.org/10.1007/s10291-024-01694-8>
- Mkoy, L. M., Elifuraha, S., & Tarimo, B. C. (2024). Soil moisture content estimation using GNSS-IR method in Tanzania. *Boletim de Ciências Geodésicas*, 30, e2024021. <https://doi.org/10.1590/s1982-21702024000100021>
- O'Neill, P. E., Chan, S., Njoku, E. G., Jackson, T. J., Bindlish, R., Chaubell, J., & Colliander, A. (2023). *SMAP Enhanced L3 Radiometer Global and Polar Grid Daily 9 km EASE-Grid Soil Moisture, Version 6*. NASA National Snow and Ice Data Center. <https://doi.org/10.5067/M200XIZHY3RJ>
- Ochsner, T. E., Cosh, M. H., Cuenca, R. H., Dorigo, W. A., Draper, C. S., Hagimoto, Y., Kerr, Y. H., Njoku, E. G., Small, E. E., & Zreda, M. (2013). State of the art in large-scale soil moisture monitoring. *Soil Science Society of America Journal*, 77(6), 1888-1919. <https://doi.org/10.2136/sssaj2013.03.0093>
- Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., & Teuling, A. J. (2010). Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99(3-4), 125-161. <https://doi.org/10.1016/j.earscirev.2010.02.004>
- Small, E. E., Larson, K. M., Chew, C. C., Dong, J., & Ochsner, T. E. (2016). Validation of GPS-IR soil moisture retrievals: Comparison of different algorithms to remove vegetation effects. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 9(10), 4759-4770. <https://doi.org/10.1109/JSTARS.2015.2504527>

Zavorotny, V. U., Larson, K. M., Braun, J. J., Small, E. E., Gutmann, E. D., & Bilich, A. L. (2010). A physical model for GPS multipath caused by land reflections: Toward bare soil moisture retrievals. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 3(1), 100-110. <https://doi.org/10.1109/JSTARS.2009.2033608>