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CYGNSS SOILSCAPE SITES: SENSOR CALIBRATION AND DATA ANALYSIS

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Monitoring soil moisture enables detailed understandings of its role in the water cycle and how it is affected by climate change. Multiple airborne and spaceborne missions have been dedicated to estimating soil moisture, including Soil Moisture Active Passive (SMAP) [1], Soil Moisture and Ocean Salinity (SMOS) [2], and Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) [3]. Some other remote sensing missions have added soil moisture retrievals along with their primary goal. For instance, the primary objective of the Cyclone Global Navigation Satellite System (CYGNSS) mission [4] is wind speed retrieval over the ocean, but it is now also used for soil moisture retrieval, among other applications [5,6]. All these remote sensing systems and future systems need in situ soil moisture measurements to validate their products.

To that end, Soil moisture Sensing Controller and oPtimal Estimator (SoilSCAPE) is a system for measuring and reporting in situ soil moisture near real time [7,8]. Soil moisture is measured every 30 minutes and is published on the SoilSCAPE website (www.soilscape.usc.edu) shortly after the measurements. The SoilSCAPE system consists of two main components: a local coordinator and up to dozens of End Device (ED) nodes. The local coordinator has a solar panel, a large rechargeable battery, a small weather station, and electronics that communicate with the ED nodes and forward these measurements to the data server along with readings from the weather station. Each ED node has in situ sensors and ultra-low-power electronics powered by nonchargeable batteries, usually lasting between 14 and 24 months. Soil moisture sensors are installed at multiple locations and multiple depths at each location, which is key because doing so aids in capturing the heterogeneity of soil moisture at each site [9]. Lastly, XBee transceivers at ISM-900 MHz are used for communications between the EDs and the local coordinator, and measurements are sent from the local coordinator to the data server using an LTE/4G link.

Currently, the system has ten operational networks, seven of which are part of the CYGNSS land calibration/validation (cal/val) sites in the United States, spread over three regions shown in Fig. 1. The other three are in New Zealand.

The first US region has the sites designated as Z1 and Z4, located in the San Luis Valley, CO [7]. There are four nodes in Z1 and one operational node in Z4, and each node has four soil moisture sensors at depths of 5, 10, 20, and 30 cm. In Oct 2019, both Z1 and Z4 were installed, and the electronics were upgraded in Dec 2021.

The second region has three sites designated as JR-1, JR-2, and JR-3, and they are located in the Jornada Experimental Range [10] near Las Cruces, NM. Each site has four nodes, each of which has four soil moisture sensors at depths of 5, 10, 20, and 30 cm. These sensors were installed in May 2022. Node three of the JR-3 site is adjacent to the US Climate Reference Network (USCRN) Las Cruces station [11].

Finally, the last area is the Walnut Gulch Experimental Watershed [12], which has two sites: Kendall with nine nodes and Lucky Hills with seven nodes. This area is located near the town of Tombstone in southeastern Arizona. Each node has four soil moisture sensors at depths of 5, 15, 30, and 50 cm. The sensors at Kendall and Lucky Hills were installed in 2015 and were operational until Oct 2019. Later, they were revived in Aug 2022.

In New Zealand, the three SoilSCAPE sites are Wharekapua with five nodes, Ararimu with five nodes, and Riverhead with three nodes. Each node has four soil moisture sensors installed at depths of 5, 10, 20, and 30 cm. The Wharekapua and Ararimu

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sites were installed in Apr 2022, and the Riverhead site was installed in Sep 2022. These three sites were installed to support the Rongowai airborne global navigation satellite-reflectometry (GNSS-R) mission [13].

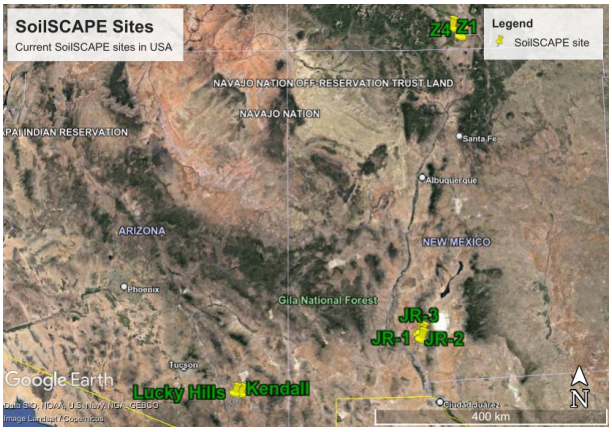


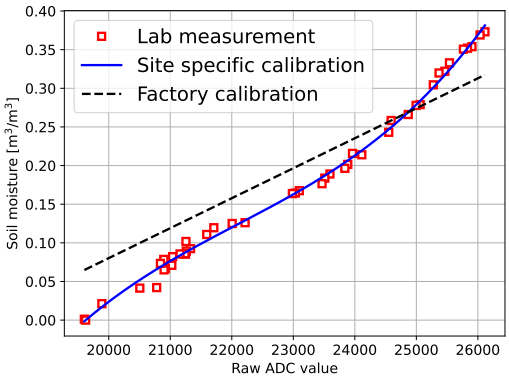
Fig. 1. CYGNSS SoilSCAPE land calibration and validation sites in the US.

In this work, we present the CYGNSS land cal/val sites, discuss sensor calibration, and show the analysis of some of the soil moisture measurements. In a previous work [7], soil temperature and moisture results of both Z1 and Z4 sites were presented.

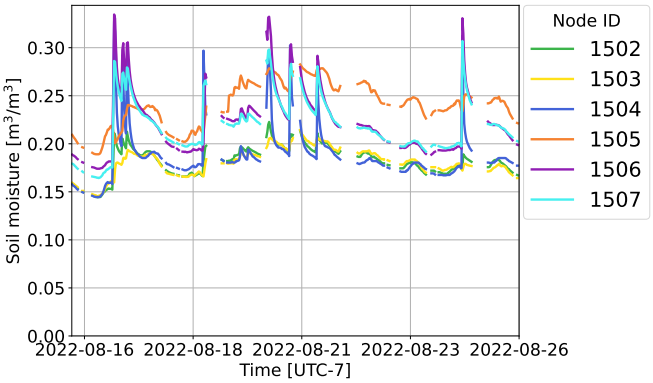
Current sites use TEROS12 and 5TM soil moisture sensors from the METER Group, which have a factory accuracy of $\pm 0.03\,\mathrm{m}^3\,\mathrm{m}^{-3}$. This accuracy is worst for dry and near-saturation conditions. However, the accuracy can be improved to ± 0.01–$0.02\,\mathrm{m}^3\,\mathrm{m}^{-3}$ by performing a soil-specific calibration. We generated multiple calibration curves for different nodes of the SoilSCAPE sites. Fig. 2(a) shows the calibration curve of the sensors at node two of the JR-3 site, where the lab measurements are the soil moisture values calculated by measuring the weight of the soil in the lab. The figure shows that using soil-specific calibration curves improves the accuracy of the data products from these sensors.

As mentioned earlier, installing multiple nodes at each site allows the SoilSCAPE system to capture the heterogeneity of soil moisture. Fig. 2(b) presents soil moisture observations at a depth of $5\,\mathrm{cm}$ for different nodes at the Lucky Hills site. This figure shows that while the temporal dynamics in soil moisture follow generally similar patterns across the spatial extent of these observations, there are significant differences, especially in the absolute levels of soil moisture. These data are indicative of the expectations that soil moisture varies spatially, and that it needs to be captured as part of the calibration and validation process of satellite-footprint-scale soil moisture retrievals.

SoilSCAPE network measurements play a vital role in the validation of soil moisture estimation using remote sensing, as the in situ measurements serve as the ground truth. Furthermore, SoilSCAPE system can be extended to measure other parameters in both the soil and the atmosphere, for example, snow water equivalent (SWE) and aerosols presence.



(a) Calibration curve for soil moisture sensors at node 2 of JR-3.



(b) Soil moisture sensor readings at depth of $5\,\mathrm{cm}$ for different nodes at Lucky Hills.

Fig. 2. SoilSCAPE sensor calibration and sample soil moisture data.

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