# SOILSCAPE WIRELESS IN SITU NETWORKS IN SUPPORT OF CYNGSS LAND APPLICATIONS

*Ruzbeh Akbar[1], James Campbell[2], Agnelo R. Silva[3], Richard Chen[2], Amer Melebari[2], Erik Hodges[2], Dara Entekhabi[1], Chris Ruf [4], Mahta Moghaddam[2]*

[1] Department of Civil and Environmental Engineering, MIT, Cambridge, MA, USA
[2] Department of Electrical and Computer Engineering, University of Southern California, Los Angeles, CA, USA
[3]METER Group Inc. Pullman, WA, USA
[4] Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, USA

IGARSS 2020 - 2020 IEEE International Geoscience and Remote Sensing Symposium | 978-1-7281-6374-1/20/$31.00 ©2020 IEEE | DOI: 10.1109/IGARSS39084.2020.9324648

## ABSTRACT

This work presents recent field activities in support of the NASA CYGNSS missions' land applications. Land reflected GNSS signals are known to be sensitive to surface topography, vegetation cover, and soil moisture. To better understand CYGNSS sensitivity to surface conditions, especially freeze-thaw states, two SoilSCAPE wireless *in situ* network sites were deployed in the San Luis Valley (SLV), CO, in late Oct. 2019. These sites capture similar weather and climatic conditions but have contrasting topography and vegetation cover. Initial analysis of CYGNSS Signal-to-Noise (SNR) observations over SLV indicates the need to fully account for land-scape topography. To this end, a forward wave scattering model that incorporates a Digital Elevation Model (DEM)is currently being developed to help explain the effects of local topography on SNR observations.

***Index Terms*—** CYGNSS, GNSS, soil moisture, signal-to-noise ratio, remote sensing, freeze-thaw, Wireless Sensor Networks

## 1. INTRODUCTION

The Cyclone Global Navigation Satellite System (CYGNSS) [1] is a constellation of 8 microsatellites designed to measure and determine tropical ocean surface wind speeds. CYGNSS measures reflected GPS signals that are scattered from ocean surfaces. Although the primary objective of CYGNSS is for ocean applications, the mission also collects GNSS reflections over land.

Land-reflected GNSS signals are known to be sensitive to a wide variety of surface conditions, especially surface topography, vegetation cover and soil moisture content [2]. Recently, a number of studies have demonstrated surface soil moisture estimation using land-reflected GNSS observations [3]–[5].

In this study, we explore the sensitivity of CYGNSS GNSS measurements to surface soil moisture and temperature. Specifically, we seek to better understand the measurements' sensitivity to soil freeze and thaw states. To support this study, in late Oct. 2019 two *in situ* sensor networks were installed in South-central CO that record and report near-real time surface-to-root-zone soil moisture and temperature information. Data from these networks (Section 2) will serve as ground truth information.

## 2. SOILSCAPE IN SITU WIRELESS SOIL MOISTURE NETWOK

The Soil moisture Sensing Controller and oPtimal Estimator (SoilSCAPE) [6] network is a collection of Wireless Sensor Network (WSN) clusters that record and report near-real-time surface to root-zone soil moisture information. SoilSCAPE WSNs have been deployed at multiple locations throughout the United States with clusters in California, Arizona, Colorado, New York State, and Alaska.

Each WSN, Fig. 1, consists of up to 20 battery-powered wireless End-devices (ED) each with 4 soil moisture probes installed at difference depths within the soil; typically, at 5, 10, 15, and 20 [cm]. Soil moisture data are collected every 20 [min] via the wireless EDs, and then transmitted to the

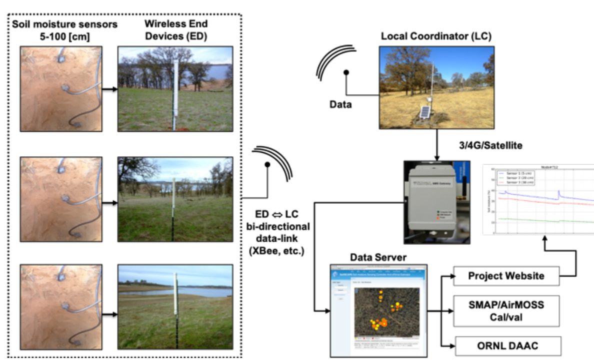



**Figure 1**. Schematic overview of a typical SoilSCAPE WSN. Soil moisture sensors are embedded within the soil and are physically connected to Wireless End-devices. EDs in turn wirelessly communicate (0.9 or 2.5 GHz ISM band) with the Local Coordinator (LC), which in turn upload data to a data-server using 3/4G or Satellite modems. Data is then distributed to end-users.

network's Local Coordinator (LC). The LC then, via 3G cellular connection, relays the data to the project's website and data server (https://soilscape.usc.edu).

To support CYGNSS Land Applications, especially soil moisture estimation and validation, as well as sensitivity to soil freeze-thaw states, two SoilSCAPE WSNs were recently installed in the San Luis Valley (SLV), CO, Fig. 2. SLV is located in South-central Colorado and is at the headwaters of the Rio Grande River. The valley is generally flat, sandy, with croplands being the dominant land cover. The average altitude is above 2.6 [km] (7600 [ft]). The CYGNSS constellation covers the globe within $\pm 37$ [deg] latitudes. Over North America, due to its high altitude, SLV is one of the limited sites that is (a) within the mission's spatial coverage and (b) undergoes soil freeze and thaw state transitions.

The first SoilSCAPE site in SLV, named Z1 (37° 11.5'N,105° 59.53'W), consists of 4 wireless EDs and spans a crop field and pasture with a radius of 750 [m]. The second site, named Z4 (37° 3.44'N 105° 49.5'W), spans a radius of 350 [m] with 5 wireless EDs. The Z4 site has more topography compared to Z1, and its land cover is grass with sparse shrubs.

Within both sites, the soil moisture and temperature sensors are installed at 5, 10, 20, and 30 [cm] depths. Furthermore, both sites include a small weather station which reports hourly precipitation, air temperature, solar radiation, wind speed, and relative humidity measurements.

## 2. INITIAL ANALYSIS OF CYGNSS SNR OVER SLV

Both *in situ* WSN sites were installed late October 2019. With the infrequent CYGNSS overpass times at these latitudes, limited data are currently available. To address this issue, CYGNSS observations within a 5 [km] radius of each site are selected. Then, from the corresponding delay-Doppler maps (DDM) the Signal-to-Noise (SNR) values were calculated. Following [7], for quality control, a threshold of 3 [dB] was selected, such that SNR > 3 [dB] are only considered. For valid SNR data points, their corresponding overpass times and incidence angles, $\theta^{inc}$ [deg], were also selected.

In situ soil moisture and temperature data are spatiotemporally averaged within ± 1 hour of each CYGNSS SNR data point. Both sites are on average very dry (soil moisture < 0.15 [-]). However, the air and soil temperatures have dropped significantly as the winter season has progressed. Since Dec. 20$^{th}$, 2019 the root-zone soil temperature profile at both sites are persistently below zero, indicating frozen soil status.

Figure 3 shows the time-series of available CYGNSS SNR observations for Z1 (top) and Z4 (bottom) from Oct. 27$^{th}$ to Dec. 31$^{st}$ 2019. SNR markers in the figures are colored proportional to their observation incidence angles which vary between 25-33 [deg]. To isolate, or minimize, the effect of varying incidence angles, for each site, the mode incidence angle over all times (most frequent) was determined and then

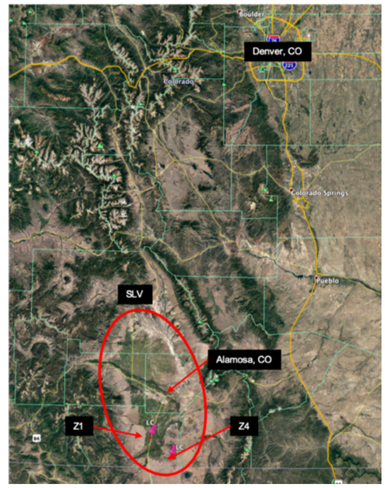
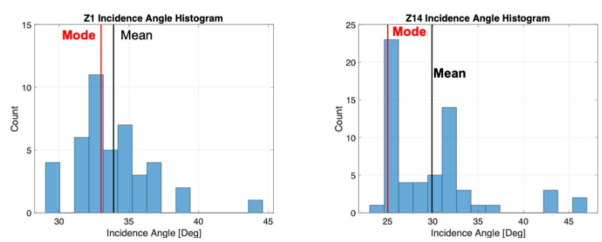



**Figure 2**. Location of the San Luis Valley in CO. The two in situ sites are labeled as Z1 and Z4. Both sites were installed and deployed late October 2019.

SNR observations within $\pm 2$ [deg] of the mode were selected, $\theta^{inc}_{Z1} \approx 33$ [deg.] and $\theta^{inc}_{Z4} \approx 25$ [deg.]. Observation angle histograms for each site is shown in Fig. 4 along with the mean (black) and mode (red) values.




(a) (b)

**Figure 4**. CYGNSS SNR observation angle histograms for (a) Z1, and (b) Z4 in situ sites. The data span 10/28/19-12/31/19.

Figure 5 shows scatter plots of these SNR values with respect to field-averaged 5 [cm] soil moisture and temperatures values. The marker colors in Fig. 5 are proportional to the 5 [cm] soil temperature. Between the two sites, the response and sensitivity of SNR to changes in temperature and soil moisture is varied. SNR observations over Z1 indicate a decreasing trend as the soil and air temperatures decrease. Observations over Z4, unlike Z1, are clustered and exhibit a vertical spread for dry soil conditions, Fig 5a. This variability maybe due to the effects of surface topography within the 5 [km] radius of the site.

## 3. DISCUSSION AND FUTURE RESULTS

To better understand CYGNSS SNR dynamics in SLV and to determine SNR sensitivity to freeze/thaw states, in addition to longer time-series of data, the effects of surface roughness and topography must be examined in more detail and isolated from soil moisture and temperature states. Topography and surface features are particularly important due to the fact that the strength of measured GNSS signals

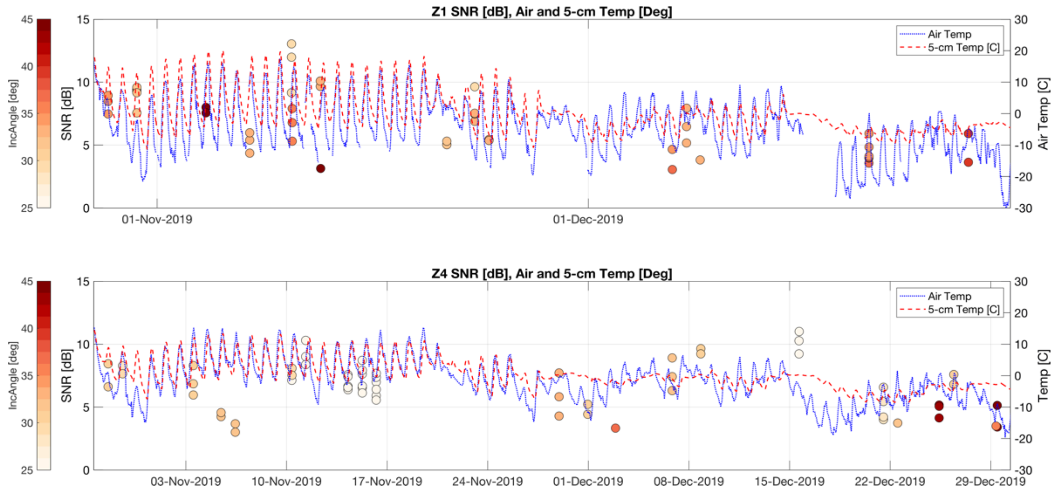



**Figure 3.** Time-series of CYGNSS SNR [dB] within a 5 [km] radius of the in-situ sites. SNR markers are colored proportional to the incidence angle [deg.]. Time-series of hourly 1 [m] Air temperature [C] (blue), and field-averaged 5 [cm] soil temperature [C] (red) is also shown.

over land are dependent on land-scape topography. Over an *in situ* site such as Z4, these effects are further compounded when observations are acquired with respect to different slopes and aspects.

To account for the observed SNR variation as function of incidence angle, topography and variable Fresnel reflectivity zones, a wave scattering model is currently being developed which incorporates a Digital Elevation Model (DEM). Results and analysis from this wave scattering model, together with comparisons to *in situ* data and CYGNSS observations will be presented.


## 4. ACKNOWLEDGMENTS

The authors acknowledge funding and support from the NASA Earth Science Technology Office (ESTO) and NASA CYGNSS project. Support and participation from the field deployment teams, and the engineering staff at the Space Physics Research Lab (SPRL) at the University of Michigan, Ann Arbor, is gratefully acknowledged.


## 5. REFERENCES


[1] C. S. Ruf *et al.*, "New Ocean Winds Satellite Mission to Probe Hurricanes and Tropical Convection," *Bull. Am. Meteorol. Soc.*, vol. 97, no. 3, pp. 385–395, Mar. 2016.

[2] A. Camps *et al.*, "Sensitivity of GNSS-R Spaceborne Observations to Soil Moisture and Vegetation," *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, vol. 9, no. 10, pp. 4730–4742, Oct. 2016.

[3] C. Chew, R. Shah, C. Zuffada, G. Hajj, D. Masters, and A. J. Mannucci, "Demonstrating soil moisture remote sensing with observations from the UK TechDemoSat-1 satellite mission," *Geophys. Res. Lett.*, vol. 43, no. 7, pp. 3317–3324, Apr. 2016.

[4] H. Kim and V. Lakshmi, "Use of Cyclone Global Navigation Satellite System (CyGNSS) Observations for Estimation of Soil Moisture," *Geophys. Res. Lett.*, vol. 45, no. 16, pp. 8272–8282, Aug. 2018.

[5] C. C. Chew and E. E. Small, "Soil Moisture Sensing Using Spaceborne GNSS Reflections: Comparison of CYGNSS Reflectivity to SMAP Soil Moisture," *Geophys. Res. Lett.*, vol. 45, no. 9, pp. 4049–4057, May 2018.

[6] M. Moghaddam *et al.*, "Soil Moisture Profiles and Temperature Data from SoilSCAPE Sites, USA." ORNL Distributed Active Archive Center, 2016.

[7] H. Carreno-Luengo, G. Luzi, and M. Crosetto, "Sensitivity of CyGNSS Bistatic Reflectivity and SMAP Microwave Radiometry Brightness Temperature to Geophysical Parameters over Land Surfaces," *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, vol. 12, no. 1, pp. 107–122, Jan. 2019.

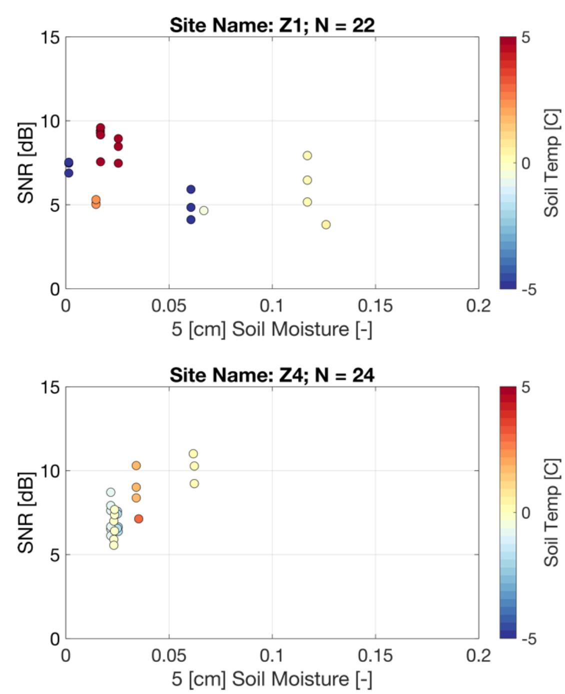




**Figure 5**. Scatter plots of CYGNSS SNR (within ± 2 [deg] of mode $\theta^{inc}$ vs. field averaged soil moisture [-] for Z1 (top) and Z (4) bottom. Marker colors are proportional to the 5 [cm] soil temperatures.