The sensitivity of ground-reflected GNSS signals to near-surface soil moisture, as recorded by spaceborne receivers

C. Chew, A. Colliander, R. Shah, C. Zuffada, M. Burgin*
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA, USA
*Corresponding author, E-mail: clara.c.chew@jpl.nasa.gov

***Abstract*—Spatial and temporal variations in near-surface soil moisture are important to measure for climate studies, numerical weather forecasts, and drought monitoring. Several previous studies have shown success in using ground-reflected Global Navigation Satellite System (GNSS) signals as a form of bistatic radar to sense soil moisture. However, the ability of this type of data to sense soil moisture variations from space is still a nascent field of study. In the past two years, three satellites have been launched that were either designed to capture ground-reflected GNSS signals or have been modified to record these signals. The data provided by these satellites are giving scientists an unprecedented opportunity to investigate their ability to detect changes in Earth's land surface, including but certainly not limited to near-surface soil moisture. This paper will present spaceborne observations of ground-reflected GNSS signals and evaluate their sensitivity to near-surface soil moisture. This sensitivity will be compared to empirical and theoretical sensitivities of monostatic L-band radar measurements to soil moisture. We will also comment on possibilities for retrieval algorithm development, using techniques employed for monostatic radar as a guide.**

Keywords—soil moisture, GNSS, GPS, bistatic radar, remote sensing

I. Introduction

Soil moisture, the amount of water contained within soil pores, is an important hydrologic and climatologic variable that is critical to measure at multiple spatial and temporal scales. Soil moisture determines the relative partitioning between sensible and latent heat fluxes and can be an important driver of convection initiation. It is also an indicator of hydrologic drought, forest fire and landslide risk, and plant health. Soil moisture remote sensing has been the subject of several satellite missions, with two being specifically dedicated to sensing soil moisture. These two missions, however, are limited to sensing soil moisture at coarse spatial scales (~36-40 km), which makes them suitable for input to global weather and climate models, for example, but severely limits their use for some other applications that require higher resolution.

The use of ground-reflected Global Navigation Satellite Systems (GNSS) and Global Positioning System (GPS) satellites as bistatic radar transmitters for land surface remote sensing is an emerging field that has increasingly gained attention over the past 15-20 years. This technique, sometimes called GNSS-Reflectometry (GNSS-R) is well suited for remote sensing near-surface (0-5 cm) soil moisture because the satellites transmit L-band microwave signals, which are transparent to clouds and are able to penetrate vegetated landscapes better than shorter wavelength signals. L-band is also the frequency that is used by the other satellites dedicated to soil moisture remote sensing, the Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) satellites. Because the transmitted signal is free, a constellation of receivers can be launched for less than the cost of one traditional monostatic radar or radiometer. This can significantly improve the temporal repeat time to sub-daily observations. In addition, for smooth or relatively smooth regions of the Earth, a GNSS reflection recorded by a receiver flying on a low-Earth orbiting satellite will have a spatial resolution of less than 1 km.

It has been shown in several studies that both specialized [1] and geodetic-quality [2]–[5] GNSS antennas and receivers may be used to sense near-surface soil moisture, though until recently these types of observations were not readily available from space. However, since 2014 three new sources of spaceborne GPS reflection data have become available, which have started to be analyzed for their sensitivity to near-surface soil moisture [6], [7]. The first, TechDemoSat-1 (TDS-1), was launched in July 2014 by Surrey Satellite Technologies (SSTL). One of the payloads on TDS-1 is a GPS receiver with a 13 dB left hand circular polarization (LHCP) antenna. TDS-1 has recorded surface reflections every eight days since its launch, and SSTL has made the majority of these data publicly available. The second source of spaceborne GPS reflection data is currently being recorded by the radar receiver onboard the Soil Moisture Active Passive (SMAP) satellite. The radar receiver was not designed to record GPS signals, though shortly after the malfunction of the radar transmitter in July 2015, the receiver bandpass was retuned to the GPS L2 frequency. These data are recorded with a 36 dB rotating antenna at both horizontal and vertical polarizations. The third source of reflection data is being recorded by the Cyclone GNSS (CyGNSS) mission, a constellation of eight satellites launched in December 2016 that is orbiting the tropics. The CyGNSS satellites are flying the same receiver as TDS-1 though with a slightly higher gain LHCP antenna (~15 dB).

In this study, we use reflection data from TDS-1, SMAP, and CyGNSS to investigate the sensitivity of GNSS surface reflections to near-surface soil moisture. We compare observational data to expected changes in reflectivity due to soil moisture and use *in situ* probe data to investigate the sensitivity of spaceborne GNSS-R to soil moisture. In order to understand the utility of using spaceborne GNSS-R data to retrieve soil moisture, we compare our findings to exisiting empirical and theoretical relationships between soil moisture and backscatter, which is the more widely-accepted method to estimate moderate- to high-resolution soil moisture.

II. Methods

A. Processing of Delay-Doppler Maps

For the receivers used in this study, GNSS ground-reflections are realized in delay-Doppler Maps (DDMs), which are two-dimensional cross correlations of the received signal and a locally generated replica for different path delays and Doppler shifts. Two examples of DDMs recorded by TDS-1 are shown in Fig. 1, one recorded over the Ebro Delta in Spain (Fig. 1a) and one recorded over the Mediterranean Sea (Fig. 1b). It has been argued previously in [6] that reflections recorded over the land surface as in Fig. 1a have a strong coherent component, which means that the theoretical spatial resolution of land surface reflections is less than 1 km. In this study, we analyze land surface reflections as if they are coherent, though certainly in heavily forested or mountainous areas, this assumption will not be accurate. Thus, we limit our analysis to areas where we do not believe the vegetation water content or surface roughness to be prohibitively high, though the vast majority of *in situ* soil moisture observations tends to come from these areas as well.

Here, we calculate the peak signal-to-noise ratio (SNR) of each DDM, using a form of the bistatic radar equation that assumes coherent scattering.

$$P_p^c = \frac{P_r^t G^t}{4\pi(R_{ts}+R_{sr})^2}\frac{G_p^r \lambda^2}{4\pi}\Gamma_p \qquad (1)$$

Where: P_p^c is the received power at a particular polarization p, P_r^t is the transmitted right hand circular polarization (RHCP) power by a GPS satellite, G^t is the gain of the GPS transmitting antenna, R_{ts} is the distance between the transmitter and the specular reflection point, R_{sr} is the distance between the specular reflection point and the receiver, G_p^R is the gain of the receiving antenna, λ is the GPS wavelength, and Γ_p is the reflectivity of the surface at a particular polarization.

In terms of the DDM, P_p^c is the peak power of the DDM, which is affected by the reflectivity of the surface and thus by changes in soil moisture. We would like to solve for Γ_p in (1) which is related to the SNR of the DDM by the following:

$$SNR_p \propto \Gamma_p \propto P_p^c - N \quad + \ (R_{sr} + R_{ts})^2 \ - G_p^r \qquad (2)$$

Where: N is a noise correction computed from the median value of the power in the DDM across all values of Doppler shift pre-reflection, which corresponds to the receiver's noise. Here, all terms are expressed in dB. Note that P_r^t and G^t no longer appear in this equation—presently, we assume that the gain and transmitting power of GPS satellites does not vary, and we thus treat them like constants. In the future, however, the varying transmitting power of the L1 and L2 frequencies and satellites should be considered.

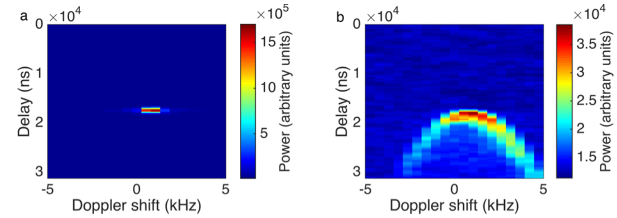

Fig. 1: (adapted from [6]) a. DDM recorded over a rice field in the Ebro Delta, Spain. b. DDM recorded over the Mediterranean Sea.

B. Comparison with Ancillary Soil Moisture

We use several sources of ancillary soil moisture data to which we compare our SNR observations. Satellite soil moisture retrievals from both SMOS and SMAP are used as well as *in situ* soil moisture probe observations where there are a sufficient number of nearby reflections. In order to disentangle the confounding effects of varying levels of surface roughness on the SNR observations, we focus on overlapping ground tracks—reflections recorded at the same or nearly the same locations but at different times, though we also present examples of gridded mean temporal changes and broader spatial correlations as well.

III. Results

Figure 2 illustrates one example of the qualitative relationship between SNR from CYGNSS reflections and the SMAP radiometer soil moisture product. Agricultural regions in both India and Pakistan, particularly the Punjab, exhibit very high SNR (Fig. 2a). These areas are also areas with relatively high soil moisture, which is shown in Figure 2b. Bangladesh, a region known for its high concentration of wetlands, is also an area where SNR is greater than 15 dB above the mean ocean value, indicating a highly reflective surface.

There are also areas in Figure 2 where the SNR does not seem to correspond well to the SMAP soil moisture retrievals,

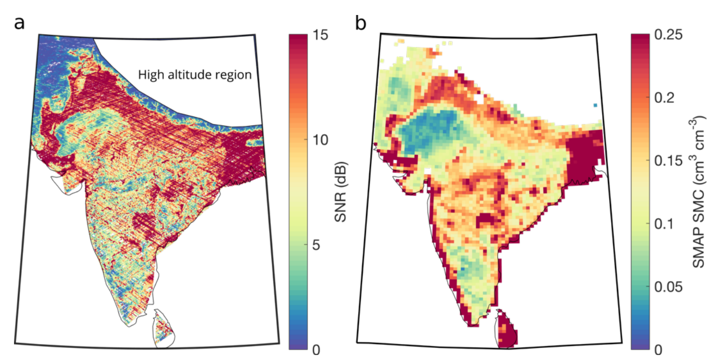

Fig. 2: a. SNR from CYGNSS data recorded from approximately mid-February to mid-March, 2017. SNR is referenced with respect to the mean value of SNR over the ocean, such that a value of 0 dB indicates an SNR equal to that typical of the ocean surface. Data over the ocean as well as data recorded from areas with altitudes >3000 m are masked out. One limitation of CYGNSS for land applications is that it cannot record data from these high altitude regions. b. SMAP Level 3 soil moisture retrievals for March 1-3, 2017 [8].

such as the region immediately south of the Punjab (the north western region of India above the peninsula), which is primarily desert. GNSS-R, like monostatic radar, is also sensitive to surface roughness changes, so flat areas of desert may exhibit high SNR even if these areas are dry. This highlights the need for a careful analysis of how SNR responds to different land cover and surface types before soil moisture retrievals using GNSS-R can be made.

There is a good relationship between temporal changes in SNR and temporal changes in the SMAP soil moisture retrievals. Fig. 3 shows collocated measurements of SNR from TDS-1 (labeled as Forward scatter) and soil moisture retrievals from SMAP. Between the two dates of acquisitions, SMAP indicates that soil moisture generally decreased, though there are one or two regions where soil moisture stayed the same or increased. These same patterns are exhibited in the SNR observations—where soil moisture increased, SNR increased; where soil moisture decreased, SNR decreased; where soil moisture remained the same, SNR remained nearly the same.

As mentioned above, the sensitivity of SNR to changes in soil moisture will change depending on the extent of surface roughness, and these changes in sensitivity need to be understood before a retrieval algorithm can be developed. This problem is also encountered in monostatic radar retrievals of soil moisture, which is discussed at length in [9]. The data cube approach to retrieving soil moisture from backscatter observations, which is presented in [9], is also the approach used to derive the soil moisture product at GPS ground stations in the western United States [3]. Given the observed sensitivity of SNR to soil moisture as well as the existing data cube methodology for soil moisture retrievals, it is possible that this approach could also be used to retrieve soil moisture for the spaceborne observations.

IV. Conclusions

Observations of SNR from spaceborne GNSS receivers are showing good sensitivity to near-surface soil moisture. If the effects of surface roughness and vegetation on SNR can be adequately modeled, it is likely that a successful retrieval algorithm can be developed. Given that the mean temporal repeat time of CyGNSS is ~3 hours and the reflected signal may have a relatively small spatial resolution, a soil moisture product derived from these observations would have a unique combination of spatial and temporal resolutions. This new data type could be used to help downscale radiometer soil moisture retrievals, or as a standalone product, which would help terrestrial hydrologists understand small-to intermediate- scale processes driving soil moisture change.

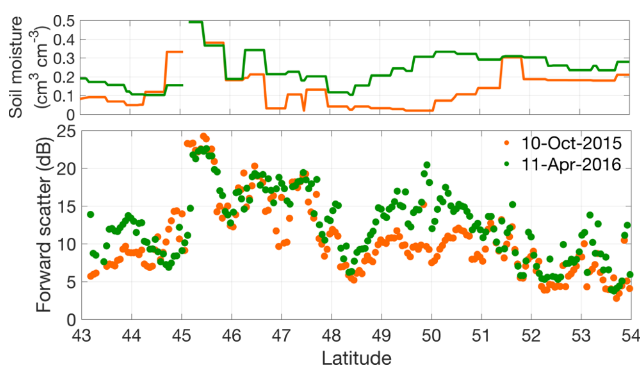

Fig. 3: Collocated measurements of SNR (forward scatter) from TDS-1 and soil moisture retrievals from the SMAP radiometer. Changes in SNR over time are indicative of changes in moisture content.

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References

[1] N. Rodriguez-Alvarez, X. Bosch-Lluis, A. Camps, A. Aguasca, M. Vall-Llossera, E. Valencia, I. Ramos-Perez, and H. Park, "Review of crop growth and soil moisture monitoring from a ground-based instrument implementing the Interference Pattern GNSS-R Technique," *Radio Sci.*, vol. 46, no. 5, pp. 1–11, 2011.

[2] E. E. Small, K. M. Larson, C. C. Chew, J. Dong, and T. E. Ochsner, "Validation of GPS-IR Soil Moisture Retrievals: Comparison of Different Algorithms to Remove Vegetation Effects," *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, pp. 1–12, 2016.

[3] C. Chew, E. E. Small, and K. M. Larson, "An algorithm for soil moisture estimation using GPS-interferometric reflectometry for bare and vegetated soil," *GPS Solut.*, vol. 20, no. 3, pp. 525–537, 2016.

[4] C. C. Chew, E. E. Small, K. M. Larson, and V. U. Zavorotny, "Effects of near-surface soil moisture on GPS SNR data: Development of a retrieval algorithm for soil moisture," *IEEE Trans. Geosci. Remote Sens.*, vol. 52, no. 1, pp. 537–543, 2014.

[5] K. M. Larson, J. J. Braun, E. E. Small, V. U. Zavorotny, S. Member, E. D. Gutmann, and A. L. Bilich, "GPS Multipath and Its Relation to Near-Surface Soil Moisture Content," vol. 3, no. 1, pp. 91–99, 2010.

[6] 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.*, pp. 3317–3324, 2016.

[7] A. Camps, H. Park, M. Pablos, G. Foti, and C. P. Gommenginger, "Sensitivity of GNSS-R Spaceborne Observations to Soil Moisture and Vegetation," pp. 1–13, 2016.

[8] P. O'Neill, S. Chan, E. Njoku, and T. Jackson, "*SMAP L3 Radiometer Global Daily 36 km EASE-Grid Soil Moisture."* Version 3. Boulder, Colorado USA: NASA National Snow and Ice Data Center Distributed Active Archive Center, 2016.

[9] P. S. Narvekar, D. Entekhabi, S. Kim, and E. G. Njoku, "Soil Moisture Retrieval Using L-Band Radar Observations," *IEEE Trans. Geosci. Remote Sens.*, vol. 53, no. 6, pp. 3492–3506, 2015.