Soil Moisture Observation Utilizing Reflected Global Navigaiton Satellite System Signals

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***Abstract*— As a new tool, GNSS-R with L-band navigation satellite signal has been applied to measure soil moisture based on its higher performance and lower cost. This paper analyzes the reflected signals from navigation satellite and the soil moisture calculation model from the electromagnetic wave polarization and dielectric constant. One ground based experiment was conducted in Beijing Vegetable Research Center for validation. Data processing result shows that the scattered GPS signals with high elevation could be used for soil moisture computation through ICF model. *In-situ* observations were compared for the further analyses in terms of measurement accuracy.**

Keywords—GNSS-R; soil moisture retrieval; remote sensing

I. INTRODUCTION

GNSS-R (Global Navigation Satellite System - Reflections) remote sensing is a new category of satellite navigation applications. Essentially, it entails a method of remote sensing that receives and processes microwave signals reflected from various surfaces to extract useful information about those surfaces. In this process, the GNSS L-band satellite acts as the transmitter and an airplane or low earth orbit (LEO) satellite, as the receiving platforms. A GNSS-R receiver can also be placed on the land [1].

Taking advantage of the high availability and stability of GNSS signals, a number of applications have been developed, most notably ocean surface wind estimation, precision ocean altimetry, sea ice condition detection, and target detection [2-6]. For land scenarios, the L-band GNSS signals are sensitive to variation of the dielectric constant of land, which is determined by the near-surface soil moisture, together with other parameters of the soil [7-9]. There are experimental evidences that GNSS reflected signals from the ground can be detected and processed to obtain soil moisture estimates.

NASA's Langley Research Center cooperated with University of Colorado to make an airborne experiment in 2000, using DMR (Delay Mapping Receiver) [10]. The results indicated that the peak power of a reflected signal is sensitive to soil moisture. They then conducted a series of experiments (SMEX02-03) [11], the initial results of which showed consistence between GPS-reflected SNR measurements and surface features [12]. In 2009, Spanish Starlab collected GNSS-R data, meteorology parameters, and vegetation parameters with the growth of sunflowers. The results demonstrate high sensitivity of reflected signals to moisture content of soil covered by vegetation [13]. In 2013, Wan Wei proposed a correction factor f_c that considers the vegetation effect [14]. In order to monitor the global soil moisture, the ultimate goal is to achieve space borne observations. Both NASA and ESA have started the task of launching satellites. SMOS launched by ESA in November 2009 can provide a resolution of 50 kilometers. In addition, NASA SMAP is scheduled for launch in 2014–2015 to make global measurements of the soil moisture with a resolution of 10 kilometers. It will be able to distinguish frozen from thawed land surfaces and is also directly applicable to flood assessment and drought monitoring [15].

However, this technology has not been applied to commercial production currently for the lack of validation of retrieval model and the limitation of accuracy. Land-based experiment was performed in Beijing by Beihang University with the assistant of Peking University and Beijing Vegetable Research Center in September 2013. The principle of soil moisture measurement, following the experiment and its data analysis results are introduced in this paper. It is concluded that a new data processing method using reflected signal wave area is valid and has good performance.

II. THEORETICAL ANALYSIS

A. Basic Principle

When electromagnetic wave meets reflecting surface in its propagation path, reflection or scattering happens, resulting in a variation in the polarization characteristics, amplitude and phase of reflected waveform, which is related to the material, area and other properties of the surface. Therefore, we can retrieve the physical information of the surface as long as the variation is detected.

In GNSS-R measurement system, the receiver is usually designed to employ a pair of antennas in order to collect the GNSS direct signals in conjunction with the reflected signals. A RHCP (Right-Hand Circular Polarized) zenith antenna collects direct GNSS signals while a LHCP (Left-Hand

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Circular Polarized) nadir antenna collects land surface reflected GNSS signals. The typical bistatic radar system mode consists of a transmitter that mounted on satellite, a reflected signal receiver, with scattering taking place mainly from the region of the surface surrounding a specular reflection point, as depicted in Fig.1. Ground based RHCP and LHCP antennas usually have low heights, resulting in an ignorable attenuation between the received signal by LHCP antenna and the land surface reflected signal. Similarly, the direct signal can be substituted for the incidence signal on land surface because of the negligible difference of the two propagation paths.

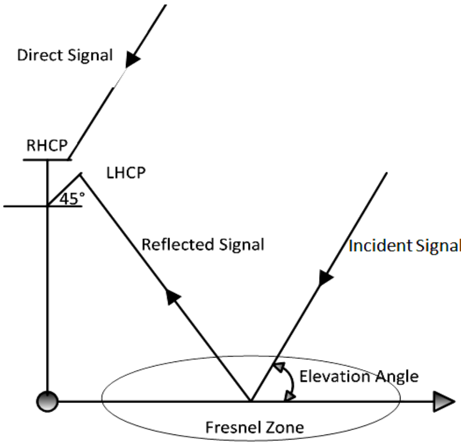

Fig. 1. Simplification of the antennas geometry

B. Retrieval model (GNSS-R observable on soil moisture)

The fundamental product of the instrument data processing chain is the so called ICF (Interferometric Complex Field), which is a time series calculated as the ratio between the reflected and direct waveform peaks, as in eqn (1), where P_R and P_D represent the time series of waveform peaks for the reflected and direct signals, respectively [16].

$$\mathrm{ICF(t)} = \frac{p_R(t)}{p_D(t)} \tag{1}$$

Reflectivity is the ratio of reflected signal to incident signal, which is replaced by direct signal in ground based experiment. The GNSS signal is mostly circular polarized, which consists of a vertical and a horizontal polarization component, as in eqn (2), (3) and (4), where θ is the elevation angle, and ε is the dielectric constant of soil [17][18].

$$R_{\perp} = \frac{\varepsilon \sin\theta - \sqrt{\varepsilon - cos^2\theta}}{\varepsilon \sin\theta + \sqrt{\varepsilon - cos^2\theta}} \tag{2}$$

$$R_{\parallel} = \frac{\sin\theta - \sqrt{\varepsilon - cos^2\theta}}{\sin\theta + \sqrt{\varepsilon - cos^2\theta}} \tag{3}$$

$$R_{RL} = \frac{1}{2}(R_{\perp} - R_{\parallel}) \tag{4}$$

Fig.2 demonstrates the change of vertical, horizontal and LHCP reflectivity with elevation under given dielectric constant of 20. For high elevation above 60 degree, increased elevation leads to ascent in vertical and LHCP reflectivity, and descent in horizontal reflectivity. And the magnitude is relatively large. Therefore, all the three kinds of reflectivity could perform well in soil moisture retrieval. On reflection, the signal would change from RHCP signal to LHCP signal, meaning that R_{RL} should be used for computation. However, experimentally, only the vertical polarization component is taken into account on derivation of the relationship between reflectivity and dielectric constant for convenience.

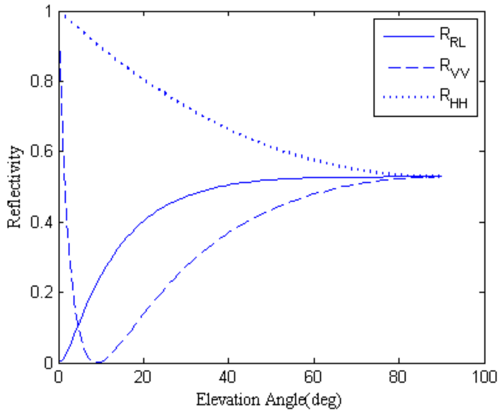

Fig. 2. Under the dielectric constant of 20, for high elevation, e.g. above 60 °, the vertical and LHCP reflectivity increase, the horizontal reflectivity descents with the increase of the elevation. The reflectivity value is 0.53 approximately and relatively large. Thus, all the reflectivity can be utilized for derivation.

In order to eliminate some random errors, calculate the average value of the above P_R and P_D sequences in the lapse of time t before computing ICF, as in eqn (5), where N is the number of waveforms computed during one data acquisition.

$$R = \sqrt{\frac{1}{N}\sum_{n=1}^{N}|\mathrm{ICF(t)}|} \tag{5}$$

Since the direct signal is relatively stable, the ICF value depends primarily on the reflected signal, and the reflection coefficient value also relies mainly on the reflected signal.

The inverse solution is obtained, as in eqn (6)

$$\varepsilon_{\mathrm{soil}} = \frac{1 \pm \sqrt{1 - 4\sin^2\theta\cos^2\theta \cdot \left(\frac{1-R}{1+R}\right)}}{2\sin^2\theta \cdot \left(\frac{1-R}{1+R}\right)^2} \tag{6}$$

In order to relate the soil reflection coefficient to soil moisture, a semi-empirical model presented in [19] could be used. The polynomial that describes the relationship between soil moisture and dielectric constant is given by eqn (7), for a frequency around 1.5 GHz where S and C are the sand and clay textural compositions of a soil in percent by weight, and the m_v is the volumetric soil moisture.

$$\varepsilon soil = 2.862 - 0.012S + 0.001C + (3.803 + 0.462C - 0.341)m_v + (119.003 - 0.500S + 0.633C)\, m_v^2 \tag{7}$$

Fig.3 illustrates the relationship between soil moisture and dielectric constant, provided that soil constituent is loam. Curves for other constituents, including sandy loam, silt loam, and silty clay, are consistent with the trend of loam. The real part of the dielectric constant ranges from 4 for dry soil to 80 for water, and is nearly proportional to soil moisture for dielectric constant greater than 5 approximately. This model has been used as a semi-empirical approach with acceptable results [20] [21].

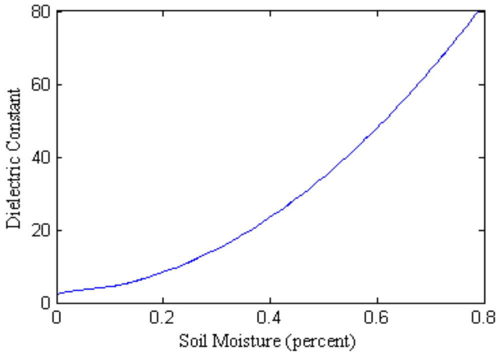

Fig. 3. Relationship between soil moisture and dielectric constant.

III. Experiment and its Results

A. Description of the Experiment

On September 18, 2013, the GNSS-R ground-based experiment was performed in Beijing Vegetable Research Center for a total of three and a half hours from 8:45 a.m. to 12:15 a.m., using GNSS-R receiver developed by Beihang University. Since the experimental field had a predominant constituent of loam and was covered by cabbages that grew evenly, it can be assumed that the soil moisture within the reflecting region was uniform at the same time. Instrument installation is shown in Fig.4.

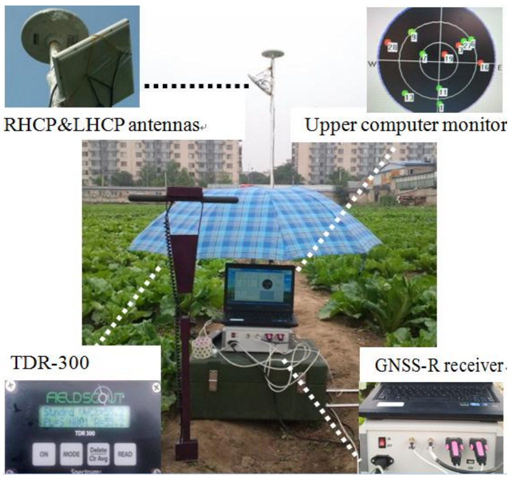

Fig. 4. System installation during ground based campaign

Ground based RHCP and LHCP antennas have low heights of 2.1m approximately which agrees with the analysis in section two. During the experiment, In-situ data was obtained by TDR-300 Soil Moisture Meter every 15 minutes, with probes of 7.5cm and accuracy of ±3.0% volumetric water content.

B. Data Processing

The obtained data consists of two parts, one is the position information and the correlation power calculated by receiver, the other is the TDR measurements.

The GNSS-R receiver was designed to choose the satellite with the highest elevation, whereby the GPS PRN19, PRN7, PRN11 and PRN1 is tracked with elevation angles range from 65° to 90° approximately, as illustrated in Fig.5.

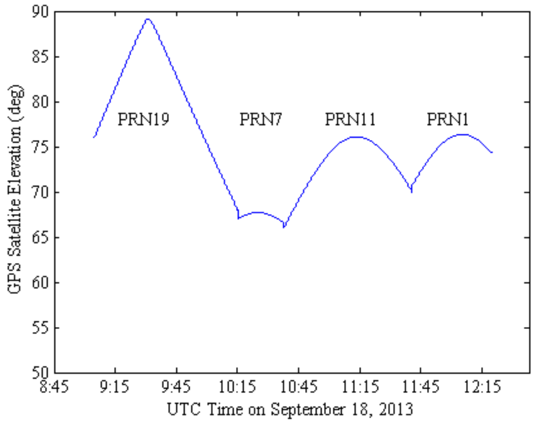

Fig. 5. Time history of the satellite elevations tracked during the experimental period.

Power measurement method of receiver is to correlate the digitized IF signal with a replica signal at a specific delay, whether it is traditional GPS receiver or GNSS-R receiver. For direct signal, the ideal shape of the correlation power is sharp triangle. However, there is a smaller peak actually with respect to reflective path delay and the attenuation of space and reflection. Along with the increase of roughness, the incoherent diffuse scattering becomes the predominant mechanism [17], and the triangular correlation power becomes smooth with a certain extension. Fig.6 represents a measured reflected correlation power waveform (8:50:40) and the discrete nature of the measurement at 1/20 code chip spacing, in which the peak power is the observable most sensitive to surface dielectric properties, and the fitting curve is computed using the exponential approximation theory.

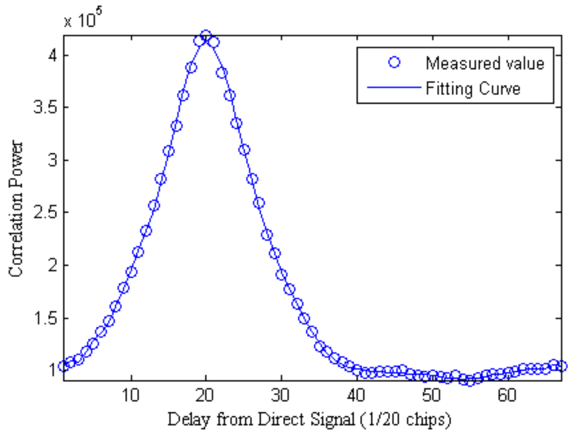

Fig. 6. Waveform of correlation power at 8:50:40 a.m.

Normalized area with the 31 1/20 chips that centre around the peak power was substituted for the waveform peak of reflected signal in eqn (1). Although the peak power presents much information of specular point, the total area below the theoretical waveform carries abundant information of fresnel zone. Surface roughness of the whole fresnel zone could influence the reflection process, which in turn determine accuracy. And because the areas far away from the specular point affect little on the reflection process, we could only consider utilizing several value nearby the peak power. There is no distinct difference between 31 1/20 chips and the total 67 1/20 chips. Then reflection coefficient retrieved by the above method shows periodic fluctuations with a period of one hour approximately and is in correspondence with the weather, as introduced in Table 1.

TABLE I. INTERMITTENT LIGHT RAINFALLS

Rainfall Condition	
Start Time	***Stop Time***
8:50	9:10 a.m.
9:43	10:14 a.m.
10:47	12:30 a.m.

The soil was reasonably moist after the precipitation event on the midnight of September 17. And during the whole study period, intermittent light rainfalls occurred once an hour approximately.

The GNSS-R soil moisture measurement is presented and compared with the *in-situ* TDR measurement in Fig.7, in which the smoothed GNSS-R value is demonstrated also. By comparison, it was found that the trend of the GNSS-R average value roughly correlates with the trend in the in-situ value, indicating the variability of the moisture is manifested in the reflected power waveform essentially. Additionally, in Fig.8, the least square method is employed to fit the GNSS-R average value to TDR data, in order to calculate the residual sum of squares, and the result is 0.0098. However, although the two curves in Fig.7 show good agreement in trend, a deviation between them is observable. And there is a relatively sharp fluctuation on the non-smoothed data. Three main factors lead to these phenomenons.

1) Length of the probes: According to [22], the GNSS-derived signal is influenced most strongly by near-surface (0–5 cm) soil moisture. However, we used TDR probes of 7.5cm to measure *in-situ* data. Soil moisture raises with the increase of depth, therefore, a larger *in-situ* value was obtained. Probes of 3.8cm could be more adoptable.

2) Vegetation cover: The reflection region was covered by vegetation of single type, the trunk and crown layer of vegetation could affect largely on the amplitude, phase and angle of scattered signal, leading to a more complicated scattering model [23]. Therefore, well-developed model to calibrate the error that caused by vegetation needs profound research.

3) Antenna radiation pattern: It is used as a reference to calculate antenna gain. From the axis of maximum radiation, passing through the center of the main lobe, antenna receives signal with larger power than from other angles. Different elevation of satellite result in different incident angle to RHCP and LHCP antennas. Therefore, the error caused by radiation pattern needs calibration.

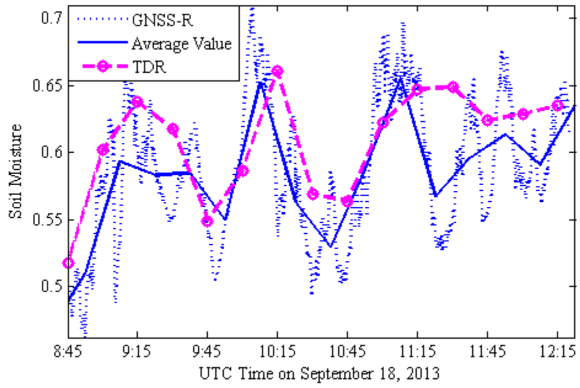

Fig. 7. Comparison between GNSS-R data and *in-situ* data. The GNSS-R soil moisture measurement is presented as dotted line. To match the dimension of the *in-situ* measurement as dotted line with little circle, the 1 Hz GNSS direct and reflected signal measurement was smoothed to mean value every 15 minutes. The mean soil moisture computed by the smoothed mean power is also plotted, using real line.

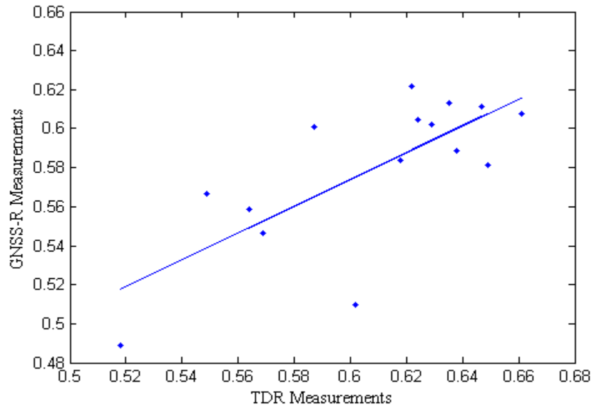

Fig. 8. Regression is suited to curvilinear character of the relationship between GNSS-R average values and in-situ measurements. Its residual sum of squares is 0.0098, which indicates good agreement in trend between them.

IV. CONCLUSIONS

The theory of soil moisture reversal based on GNSS-R technology has been presented in this paper. And a data processing method is proposed as well. Then a ground based experiment has been conducted to test and prove this idea in Beijing Vegetable Research Center in 2013. Analysis of the data collected during experiment seems to support the availability of the method in soil moisture observation.

The main conclusions of the paper include:

The GNSS-R technology with the bistatic radar system for soil moisture observation is proved to be practical. Two pairs of antennas and a special GNSS-R receiver are used to receive and process the direct and reflected signals. The scattered signal measurements follow the general soil moisture trend as a function of time. It can provide soil moisture observation in a large scale.

The new data processing method using the area below the theoretical waveform of correlation power of reflected signals seems to be valid and have good performance. Temporal changes have been observed and are proportional to varying soil moisture content with a residual sum of squares better than 0.01. And more repeatable experiments will be carried out to verify the availability of the method in the future.

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