Seasonal Polarimetric Measurements of Soil Moisture Using Tower-Based GPS Bistatic Radar

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***Abstract*- The results of GPS L-band (L1, λ = 19 cm) surface reflection measurements observed using multiple polarizations and receiving antenna gains are described. The measurements were performed using the 300-m tall ETL Boulder Atmospheric Observatory (BAO) tower during summer through fall of 2002. In this experiment the first seasonal measurements of bare soil moisture from a stationary location using bistatic reflection of signal of opportunity were performed. Several receiving antennas offering various gain and polarization sensitivities were used. Theoretical modeling of bistatic surface scattering shows that the magnitude and width of the reflected waveform depend on the dielectric permittivity of the soil, vegetation cover, and soil roughness. By observing from a fixed tower over low grass the roughness of the reflecting area remains constant, hence variations in the signal are uniquely related to changes in the dielectric permittivity, and therefore, to soil moisture. To investigate polarization sensitivity of the reflected signal to soil moisture four endfire (~ 12 dB) antennas with complete circular and orthogonal polarization sensitivities were used. The high-gain antennas increased the receiver dynamic range and reduced surface multipath radio wave interference. Seasonal retrievals of soil-moisture content from multi-polarization GPS reflection data is presented and compared with in-situ soil moisture measurements.**

I. INTRODUCTION

Knowledge of soil moisture (SM) over wide areas is essential for many applications, e.g., crop yield expectation, prediction of potential flood hazards, air quality, and local weather forecasts [1]. Remote sensing methods such as passive radiometers and active radar sensors are considered suitable for SM mapping [2-4] because conventional *in situ* soil moisture measurement techniques are both localized and expensive. To this end there are several advantages to using GPS signals of opportunity as a means of active airborne bistatic sensing of SM. Both the omnipresence of GPS signals in all weather conditions and the low cost of GPS receiver technology compared to alternative remote sensing systems makes the technique promising for widespread application. The civilian signal frequency of 1.575 GHz is also nearly optimal for SM sensing [3], with theoretical predictions [5] and initial results from experiments [6] indicating useful sensitivity to near-surface SM content.

We present here results of a stationary tower-based experiment with the goal of developing quantitative relationships between GPS reflections and soil moisture changes. The stationary tower observation geometry permits measurement of GPS reflections from the same area of land, thus excluding signal variability due to changing roughness and vegetation cover scenes.

II. MEASUREMENT TECHNIQUE

Each GPS satellite signal is coded with a unique pseudorandom noise (PRN) code designed to produce an autocorrelation function confined within ±1 code bit transition, or code "chip." Reflection of this incident signal from rough dielectric surface will produce multiple delayed signals having amplitudes proportional to the power reflection coefficient at each specular point. The output of a typical GPS reflection receiver is a cross correlation between a receiver-generated replica of the PRN code and the PRN code of the reflected signal. The cross correlation function is generally both wider and lower than the autocorrelation of the direct signal, and carries information about the roughness and dielectric properties of the soil at the specular points.

III. INSTRUMENTATION

A modified GPS navigation receiver mounted on top of the 300-meter NOAA ETL Boulder Atmospheric Observatory (BAO) tower near Erie, CO (40°03′00.1″N, 105°00′13.8″W) was used from May through December 2002 to receive both direct and reflected GPS signals. The receiver, provided by the NASA Langley Research Center, tracked the direct line of sight satellites using a low-gain zenith-oriented right hand circularly polarized (RHCP) antenna and recorded the cross correlation function of the reflected signals using an alternating series of surface-oriented antennas. The surface antennas consisted of a low-gain hemispherical left hand circularly polarized (LHCP) antenna and four endfire high gain (~ 12 dB) antennas with complete orthogonal and circular polarization sensitivities (V, H, LHCP, and RHCP). The orientation of all surface-looking antennas was 35° from nadir for the incident angle, and 245° for the azimuthal angle. The specular reflection points on the land surface created a set of diurnally repeatable ground tracks. Cross correlation waveform amplitudes were recorded only for satellites with reflection ground tracks passing through the high-gain antenna footprint of size ~ 400 m x 350 m. The cross correlation waveforms were continuously recorded in 21 quarter-chip bins for one satellite per time. Signals from the surface-looking antennas were sequentially selected using a microwave PIN switch which provided an 8 s total integration period for the low-gain LHCP antenna and a 2 s total integration period for the other antennas.

Accumulation of signals was performed in hardware for fundamental sampling intervals of 1 ms. Batches of length 0.1 s of the sum-square of the in-phase and quadrature waveform components were averaged prior to archival. To suppress high-frequency Rayleigh fading due to rough surface scattering an additional averaging of the reflected waveforms (after subtracting the noise floor) was performed over a 100-s moving window. Since the distance from the receiver to the specular point in the center of the footprint was only ~ 400 m the effect of correlation function widening due to surface roughness was negligible, and recorded waveforms occupied 2-chip intervals similar to the direct signal. The absence of widening allowed us to increase the SNR by averaging over 7 quarter-chip bins covering the entire waveform peak, instead of taking just the peak value. The time series of these averages represented the final output data (for more details see [7]).

We estimated the volumetric SM fraction at 6.0 cm depth using a Campbell Scientific CS-615 time-domain reflectometer. Probe calibration was performed by drying and weighing in-situ soil samples. The soil in the uppermost 1.0 m layer at the BAO is heavy clay.

IV. DATA ANALYSIS

The reflected signal was analyzed for several days preceding four local rain events and immediately afterwards. An expected rise of the reflected signal power was observed after rain events and subsequent decreases during following dry periods. An example of such behavior for waveforms from high-gain LHCP antenna is presented in Fig. 1. Analogous correlation with rain events was found for other polarization channels. The highest levels of reflected power were the result of a very wet top layer saturated with water or, in some instances, standing water. We also found a correlation between reflected GPS signal power and *in situ* SM measurements made on days without rain events as water was absorbed by the soil. Examples of such data obtained from GPS satellite PRN#18 using various antennas are presented in the scatter plots of Figs. 2-5.

The highest waveform SNR is obtained using the high-gain LHCP antenna (see Fig. 2) with the SNR reaching 50 for 0.33 volumetric moisture content (VMC) and leveling at 10-20 between 0.13 and 0.27 VMC. A similar behavior is exhibited by data obtained using other polarization channels, however, at lower SNR levels. The lowest SNR obtained using the high-gain antennas is (as expected from theory) produced by the RHCP antenna (Fig. 3), although an encouraging result is obtained using even the low-gain hemispherical LHCP antenna (see Fig. 5). Despite the low gain and possible complications due to multipath interference the shapes of the scatter plots are consistent for all antennas.

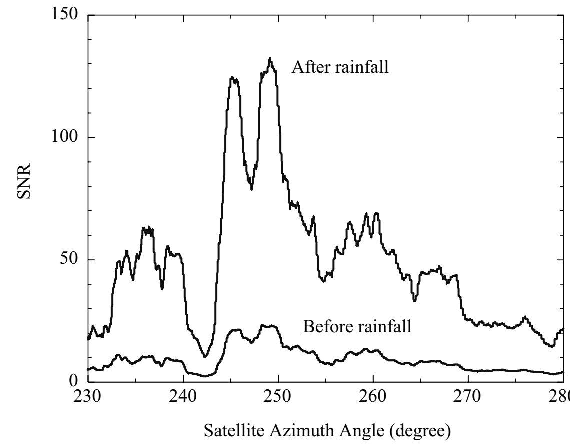

Figure 1. Comparison between two reflected signals for GPS PRN#18 obtained on July 10, 2002 before rainfall, and on July 11, 2002 after rainfall.

We note that the SNR data presented do not show significant sensitivity to the measured VMC at lower levels of moisture. A possible explanation for this follows: since the soil moisture probe was buried to only 6 cm depth there is no information about the distribution of moisture at larger depths. The L-band waves can thus penetrate through the relatively thin and dry layer to deeper soil with larger absorption. It is thus suggested that the probe SM measurements are not representative for depths important for L-band radio wave propagation.

A theoretical description based on a homogeneous soil model assumed the received signal power [5] to be

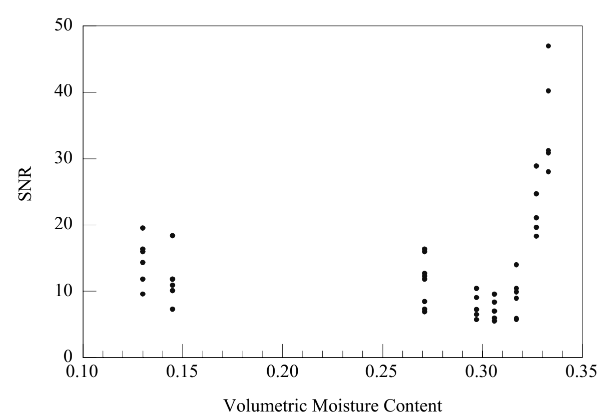

Figure 2. GPS reflection data for PRN#18 from the high-gain LHCP antenna versus *in situ* measured values of soil moisture.

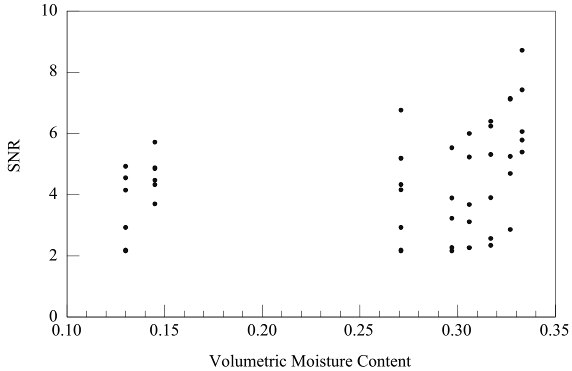

Figure 3. GPS reflection data for PRN#18 from the high-gain RHCP antenna versus *in situ* measured values of soil moisture.

proportional to the product of two factors: a polarization sensitive factor dependent on soil dielectric properties and a polarization insensitive factor dependent on surface roughness. The ratio of averaged signals powers received in two orthogonal polarizations thus tends to exclude the surface roughness factor (together with variations in illuminating power) while retaining the soil moisture signal. Calculations of such ratios using the current data, however, do not support this hypothesis. It is likely that the initial assumption about soil moisture homogeneity is too crude, and more accurate modeling of the soil moisture depth profiles is required to reproduce the measured data.

V. Conclusions

Several conclusions can be drawn from the preliminary analysis of a small fraction of the BAO data. First, an expected correlation between strong reflected signals and rain events has been observed. Second, a high level of correlation has been found between reflected signal power and *in situ* soil moisture measurements for high levels of moisture when the top layer of soil of about 6 cm of thickness was moist enough. For drier top layers the correlation between top-layer moisture and the reflected power is diminished due to deeper

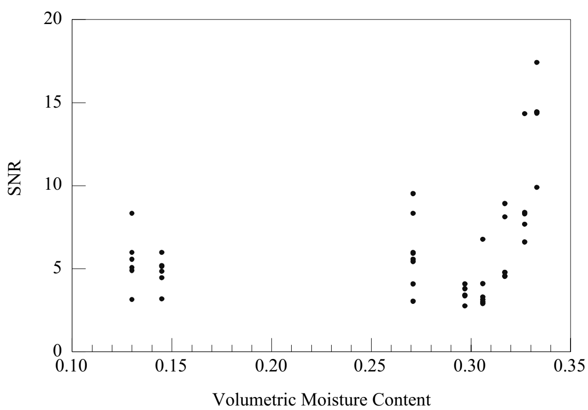

Figure 4. GPS reflection data for PRN#18 from the high-gain VP antenna versus *in situ* measured values of soil moisture.

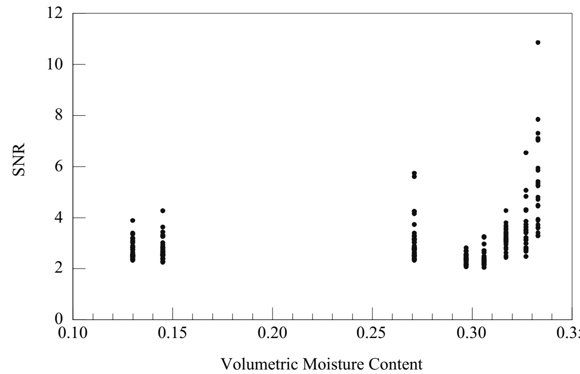

Figure 5. GPS reflection data for PRN#18 from the low-gain hemispherical LHCP antenna versus *in situ* measured values of soil moisture.

penetration of the L-band radiowaves toward the more moist and absorptive layers of soil.

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