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ORIGINAL ARTICLE

Using GPS multipath to measure soil moisture fluctuations: initial results

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Abstract Measurements of soil moisture are important for studies of climate and weather forecasting, flood prediction, and aquifer recharge studies. Although soil moisture measurement networks exist, most are sparsely distributed and lack standardized instrumentation. Measurements of soil moisture from satellites have extremely large spatial footprints (40–60 km). A methodology is described here that uses existing networks of continuously-operating GPS receivers to measure soil moisture fluctuations. In this technique, incoming signals are reflected off and attenuated by the ground before reception by the GPS receiver. These multipath reflections directly affect signal-to-noise ratio (SNR) data routinely collected by GPS receivers, creating amplitude variations that are a function of ground reflectivity and therefore soil moisture content. After describing this technique, multipath reflection amplitudes at a GPS site in Tashkent, Uzbekistan are compared to estimates of soil moisture from the Noah land surface model. Although the GPS multipath amplitudes and the land surface model are uncalibrated, over the 70-day period studied, they both rise sharply following each rainfall event and slowly decrease over a period of ∼10 days.

Keywords GPS · Multipath · SNR · Soil moisture

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Introduction

Precipitation is temporarily held at the earth's surface as soil moisture before water returns to the atmosphere via evapotranspiration, flows to rivers, or infiltrates to groundwater. In addition, antecedent soil moisture controls the partitioning of rainfall into runoff and infiltration. Therefore, soil moisture storage is a fundamental component of the terrestrial hydrologic cycle (Robock et al. 2000). Soil moisture fluctuations are a key signature of the vadose zone hydrology at a given location (Kurc and Small 2005; Teuling et al. 2006). Soil moisture dynamics influence the ecosystem response to climate variability and change, feedbacks between the land surface and atmospheric elements of the climate system, recharge of groundwater aquifers, and flood magnitude and frequency (Rodriguez-Iturbe 2000; Entekhabi and Rodriquez-Iturbe 1994; Small 2005). Accordingly, soil moisture is typically a state variable in hydrologic, ecological, and climate models, e.g., Mahfouf et al. (1996), and values are sought for model initialization and data assimilation purposes.

Local soil moisture monitoring networks do exist (e.g., http://www.okmesonet.ocs.ou.edu/), but these data are plagued by several problems. First, direct measurements of soil moisture (via extraction and drying) are labor intensive and destructive, thus indirect measurements are used if continuous measurements are desired. Second, soil moisture exhibits large spatial and temporal variations, e.g., Bhark and Small (2003), so individual point measurements are of limited use in many applications. Third, most direct and indirect measurement methods provide estimates at small scales (∼10–100 cm) whereas modeling applications require data representative of larger scales (0.1–10 km). At the other extreme, remotely-sensed measurements of soil moisture represent larger scales (40–60 km), but these data lack the spatial resolution to be useful for most applications.

In this paper a method is outlined by which soil moisture fluctuations could be estimated using standard GPS receivers. GPS stations have the potential to provide a large network of observations with individual spatial scales of 10–40 m. For example, the EarthScope (http://www.earthscope.org) plate boundary observatory will have 1,000 GPS stations operating throughout the western US and Alaska. GPS receivers are sensitive to soil moisture because all GPS antennas receive some energy from reflected signals. Here, preliminary results are presented that demonstrate how the reflected GPS signal at a site varies through time consistently with soil moisture fluctuations that are expected to accompany individual rainfall events and subsequent dry-down periods.

Methodology

Multipath occurs when an electromagnetic signal arrives at an antenna, not along a direct path, but via an indirect path due to reflection of the signal by an object or surface near the antenna. Multipath contaminates GPS measurements because the tracking loop inside the receiver locks onto a signal that is a composite of both the direct and reflected signal. It is difficult to isolate the effects of multipath in GPS carrier phase observable because of the need to model orbits, atmospheric delays, clocks, and positions in a least squares analysis. However, signal-to-noise ratio (SNR) data computed by the GPS receiver are also impacted by multipath and provide an alternative method for quantifying multipath effects.

The equations needed to describe specular (reflection from a smooth surface) multipath effects in SNR data are straightforward. Under the simplified model of GPS signal tracking in the presence of the direct plus one reflected signal, SNR at any instant is described by:

$$\mathrm{SNR}^2 = A_\mathrm{d}^2 + A_\mathrm{m}^2 + 2A_\mathrm{d}A_\mathrm{m}\cos\psi \qquad (1)$$

where A_m and A_d are the amplitudes of the multipath and direct signal, respectively, and ψ is the phase difference between the two signals (Fig. 1). As a GPS satellite passes overhead, the reflection geometry and ψ change, creating oscillations in SNR magnitude.

The frequency of these SNR oscillations depends on the satellite-reflector-antenna geometry. To simplify analysis, the reflectors studied here are restricted to approximately horizontal surfaces such as the ground beneath a GPS antenna. For a simple horizontal planar reflector and GPS signal with wavelength λ, the oscillation frequency depends on the vertical distance between the antenna and

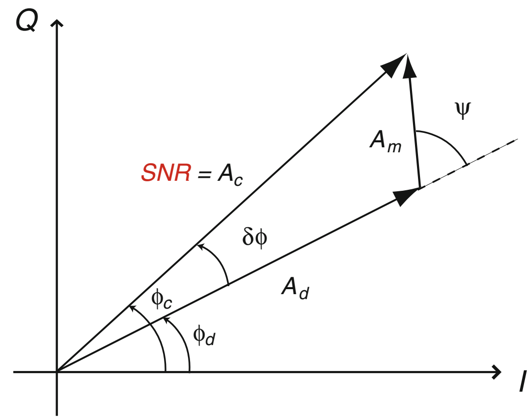

Fig. 1 GPS signal phasor diagram describing carrier tracking loop operation with a direct and reflected signal. The I and Q axes indicate in-phase and quadrature components of the signal, respectively. The three phasors represent the direct, multipath, and composite signals, with amplitudes A_d, A_m, and A_c, respectively. The phase of the direct signal is ϕ_d and the phase of the composite is ϕ_c. The multipath relative phase is ψ

the reflecting surface (h), the elevation angle of the GPS satellite (θ) and its time rate of change ($\mathrm{d}\theta/\mathrm{d}t$) (Fig. 2):

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = 4\pi\frac{h}{\lambda}\cos\theta\frac{\mathrm{d}\theta}{\mathrm{d}t} \qquad (2)$$

This means that there will be high multipath frequencies at low elevation angles and lower multipath frequencies at high elevation angles given the same reflecting surface. It also shows that h directly influences multipath frequencies, with antennas far above the ground having higher multipath frequencies than antennas closer to the ground. This equation is further simplified by making a change of variable ($x = \sin\theta$) in Eq. 2:

$$\frac{\mathrm{d}\psi}{\mathrm{d}x} = 4\pi\frac{h}{\lambda}. \qquad (3)$$

The modified frequency is constant for a horizontal reflector.

Whereas the frequency of SNR oscillations depends on surface-antenna geometry, the amplitude of SNR oscillations depends largely on surface reflectivity. Reflectivity can be related directly to an effective L-band dielectric constant via the Fresnel equations (Ulaby et al. 1986; Njoku and Entekhabi 1996). At GPS frequencies (1.57542 and 1.2276 GHz), this effective surface dielectric constant is a strong function of the soil moisture content in the upper few centimeters, with a lesser dependence on vegetation and soil type (Njoku and O'Neill 1982; Ulaby et al. 1986; Njoku and Entekhabi 1996). Thus, when a fixed area of the ground with unchanging soil composition is probed, variation in the amplitude of SNR oscillations can serve a proxy for changes in near surface soil moisture.

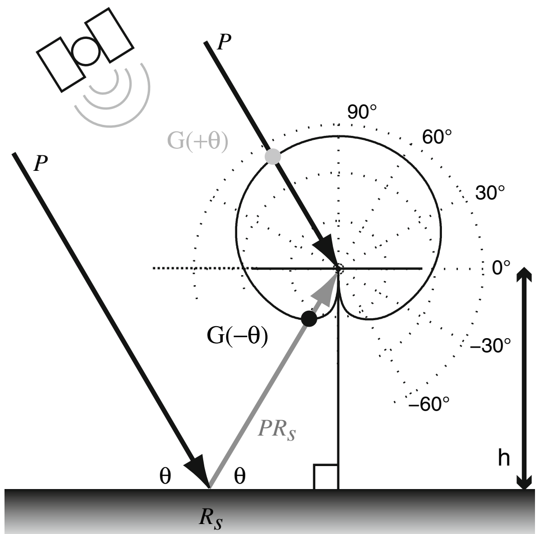

Fig. 2 Geometry of a single ground-bounce multipath signal and effects on signal power, for antenna height *h* and satellite elevation angle *θ*. Concentric *dashed circles* indicate power levels of receiving antenna gain pattern *G* (*solid line*), while *arrows* indicate GPS signal paths. For an incoming GPS signal of power *P*, the direct signal will pierce the gain pattern at an angle equivalent to the satellite elevation angle, so that $A_d = PG(+\theta)$. A parallel incoming signal will be reflected from the ground and attenuated by a reflectivity factor R_s. Assuming perfect specular reflection, the attenuated, multipathed signal will enter the gain pattern at the negative (below-horizon) satellite elevation angle, so that $A_m = (PR_s)\ G(-\theta)$. In general, $G(+\theta) >> G(-\theta)$. Gain pattern pierce points are indicated by *large filled circles*, with elevation angles marked on the outside ring

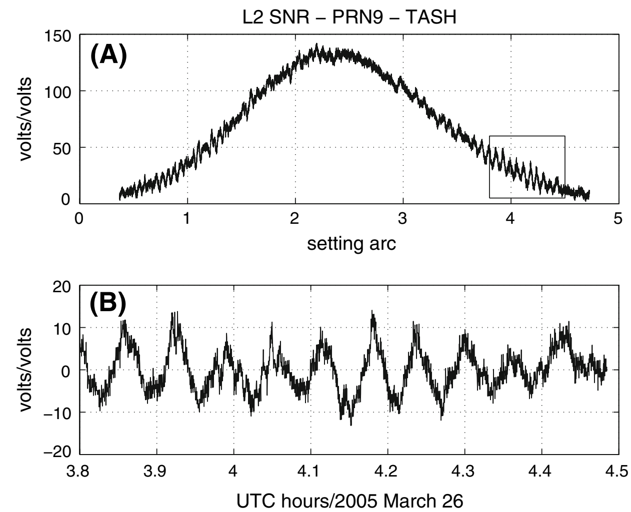

Fig. 3 **a** L2 SNR data for satellite (PRN) 9 at TASH on 2005 March 26; **b** SNR data for setting satellite with direct signal contribution removed with a low-order polynomial

To determine the SNR multipath amplitude, the multipath contribution to SNR must be separated from the direct signal's magnitude. This is done by recognizing the effects of the receiving antenna's gain pattern on recorded signal strength (Fig. 2). These gain pattern effects dictate that $A_m \ll A_d$; combined with Eq. 1, this means the multipath contribution to SNR is small in magnitude but oscillatory while A_d is large in magnitude but goes through a complete cycle only once over a satellite pass (Fig. 3a). Recognizing that the large-magnitude trend is equivalent to A_d and removing it, the multipath contribution to SNR is isolated; gain effects are accounted for by removing a low-order polynomial, revealing multipath oscillations whose amplitude is proportional to the surface reflectivity, i.e., $A_m \propto R_s$ (Fig. 3b).

For a soil moisture application, it is also important to know the location of the multipath reflection point relative to the monument, i.e., the distance and direction (azimuth) of the piece of ground radiating energy. Once again for a horizontal surface:

$$r = \frac{h}{\tan\theta} \tag{4}$$

where *r* is the radial distance. Figure 4 shows the distance to the reflection point for antenna heights varying from 1.5 to 5.0 m. The particular quadrant (north–east–south–west) of the ground being sensed depends on where the GPS satellite is in the sky.

The GPS test site used in this study is TASH (Tashkent, Uzbekistan, http://www.gfz-potsdam.de/pb1/gpsnet/). This station operates an AOA–ACT receiver with a choke-ring antenna at one sample/second. We chose this site because the SNR data for the AOA–ACT receiver are high quality (Bilich 2006) and because it is located in a region with nearby rainfall sensors. In this study only the L2 SNR data are used, although in principle, both frequencies will be affected by multipath. At TASH the antenna is mounted on a ∼6 m pillar. Figure 3a shows the quality of typical TASH SNR data for a single satellite pass, while Fig. 3b shows multipath oscillations after removing the direct signal. To compute A_m, the SNR data are first resampled according to Eq. (3) yielding several cycles of SNR data with constant $d\psi/dx$. A FFT is then computed, with the peak A_m reported for ground reflection frequencies.

Soil moisture modeling

The Noah land surface model (Chen and Dudhia 2001) is used to provide an estimate of soil moisture fluctuations at the TASH site for comparison to the GPS A_m estimates. The focus of this comparison is the magnitude and timing of fluctuations resulting from particular rainstorms, not the absolute magnitude of the signal.

The Noah model uses surface meteorological inputs to estimate the evolution of soil moisture over time. The soil hydrology component of the Noah model solves the diffusion form of the Richards equation in one dimension. The latent, sensible, and long-wave heat fluxes at the land surface are determined to conserve both mass and energy based on a Penman type combination equation. The absolute value of simulated soil moisture is sensitive to several difficult to estimate land surface parameters, e.g., soil hydraulic properties, and is not the focus of the comparison here. The Noah model was run in the offline mode, using atmospheric boundary conditions measured near the ground surface, with locally measured air temperature, pressure, humidity, and rainfall. These values were only available on a daily basis, and were interpolated to match the time-step of the model. Minimum and maximum air temperatures were available, and a sinusoidal interpolation was used for these data. Because local measurements of radiation do not exist at TASH, downward short- and long-wave radiation data from the global land data assimilation system [GLDAS (Rodell et al. 2004)] were used.

Model parameters were specified using the default values for the observed land surface types. Grassland land cover type was used with sandy loam soil hydraulic properties. Using the default sandy loam soil properties introduces a large source of error because natural variability of soil hydraulic properties has been shown to have a large impact on model simulations (Gutmann and Small 2005, 2007), but we used the default untuned model to provide the most objective estimate of soil moisture. The actual soil hydraulic properties will have a large impact on the absolute value of simulated soil moisture, but will have less impact on the timing and relative magnitude of soil moisture fluctuations.

Results and discussion

TASH A_m results for two satellites (PRN 1 and 9) for the rainy seasons (March and November) in 2005 are shown in Fig. 4. These satellites were chosen because the GPS station operators confirmed that the region sensed by these satellites (southwest of the monument) was soil. These satellites' reflection points overlap within a half-meter at elevation angles between 15° and 30°.

Also shown in Fig. 5 are modeled values of volumetric water content. The simulated soil moisture values displayed are averaged over the top 5 cm of the soil column. The daily precipitation values shown are from an airport located 8 km from the GPS site. The GPS A_m values and simulated soil moisture vary similarly through time: both rise sharply following each rainfall event and then slowly decrease over a period of ~10 days. These GPS-measured and simulated fluctuations are consistent with near-surface soil moisture dynamics in semiarid environments (Kurc

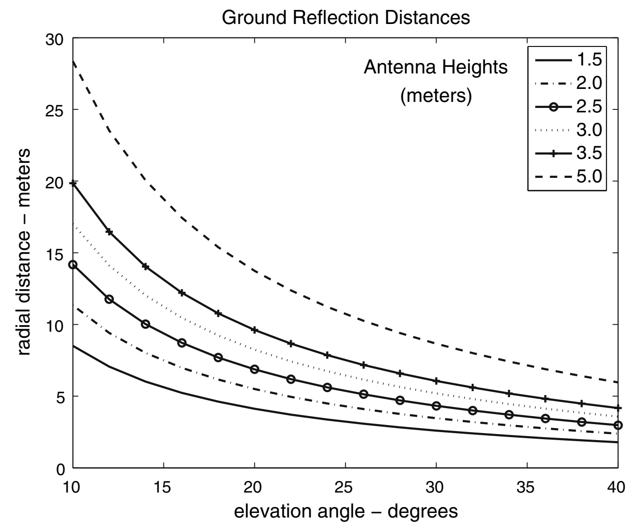

Fig. 4 Multipath reflection points as a function of GPS antenna height

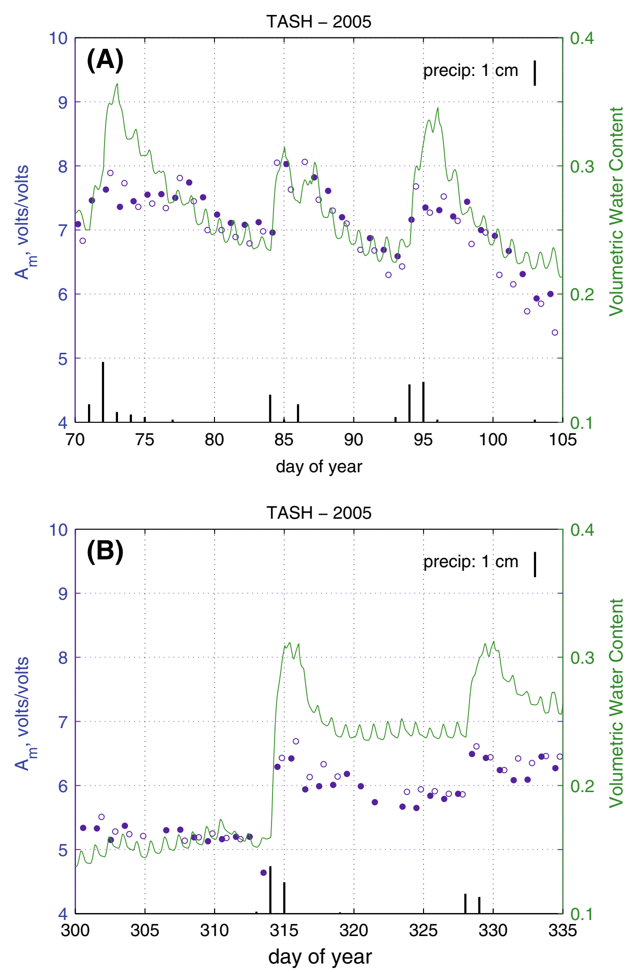

Fig. 5 Comparison of GPS multipath amplitudes and volumetric water content. *Open circles* are PRN 1 and *closed circles* are PRN 9. Daily precipitation values from a nearby airport are shown for comparison. **a** days 70–105; **b** days 300–335

and Small (2005)). The magnitude of the measured and simulated fluctuations does not always match, and this may be due in part to the lack of information regarding model parameters and rainfall intensity. For example, a 20 mm rain event that occurs in half an hour is likely to lead to a smaller increase in soil moisture than a 10 mm rain event that is spread over 5 h.

While in general the two satellites give comparable results, the estimates are slightly offset from each other, which may reflect real diurnal variations, temperature effects, or calibration effects due to differences in A_d during these time periods. Overall, the ability of GPS to track precipitation events and the accompanying soil moisture dry-down is encouraging. Future studies will focus on calibrating GPS reflectivity values by comparing with in situ data that are not available for TASH. Snow, temperature and vegetation effects are not considered here, but certainly will influence the GPS reflectivity measurements. The land surface model could be improved by having direct knowledge of the soil type and better meteorological data. The GPS estimates A_m shown here are complementary to airborne GPS reflection studies (Masters at al. 2004; Katzberg et al. 2006) that also showed sensitivity to soil moisture changes. The advantage here is that existing instrumentation that operates continuously can be utilized.

Conclusions

It has been shown that uncalibrated GPS multipath amplitude variations at a single GPS site correlate well with nearby precipitation records and land surface model predictions for soil moisture fluctuations. While these results are encouraging, further study is needed to determine the effects of vegetation, snow, temperature, and soil type on GPS multipath amplitudes If these issues and other technical issues related to receiver/antenna differences can be resolved, the GPS constellation of 30 satellites could routinely measure soil moisture fluctuations as satellites rise and set throughout the day.

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