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Use of GPS receivers as a soil moisture network for water cycle studies

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[1] Measurements of soil moisture, both its global distribution and temporal variations, are required to study the water and carbon cycles. A global network of *in situ* soil moisture stations is needed to supplement datasets from satellite sensors. We demonstrate that signals routinely recorded by Global Positioning System (GPS) receivers for precise positioning applications can also be related to surface soil moisture variations. Over a three month interval, GPS-derived estimates from a 300 m^2 area closely match soil moisture fluctuations in the top 5 cm of soil measured with conventional sensors, including the rate and amount of drying following six precipitation events. Thousands of GPS receivers that exist worldwide could be used to estimate soil moisture in near real-time, with L-band signals that complement future satellite missions.

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1. Introduction

[2] Soil moisture is fundamental to land surface hydrology, affecting flooding, groundwater recharge, and evapotranspiration [*Viterbo and Betts*, 1999]. It also influences weather and climate via its influence on turbulent and radiative fluxes between the land surface and atmosphere [*Entekhabi and Rodriguez-Iturbe*, 1994]. The water status of land plants and microorganisms is partly regulated by soil water, so soil moisture is a key component of the terrestrial carbon cycle [*Howard and Howard*, 1993]. Accordingly, soil moisture is usually a state variable in hydrologic [*Rodriguez-Iturbe*, 2000], ecological [*Running*, 1994], and climate models [*Robock et al.*, 2000]. The global distribution and temporal variations of soil moisture are sought both for analyses and modeling purposes.

[3] There is no global soil moisture dataset that fulfills the needs of the hydrology, climate, and ecology communities [*National Research Council*, 2007]. Soil moisture is measured *in situ* at many locations, both as part of individual studies or as part of monitoring networks. While these measurements are useful for small-scale or regional efforts [*Kurc and Small*, 2004; *Findell and Eltahir*, 1997; *Famiglietti et al.*, 1999], their utility for spatially-distributed studies is limited for several reasons. First, translation of soil moisture data between sensor types or from different sampling protocols is challenging. Second, horizontal variability of soil moisture is significant [*Western et al.*, 2002], but only a single vertical profile of sensors is installed at many sites (e.g., http://www.wcc.nrcs.usda.gov/scan) and most probes are only sensitive to soil conditions in a small volume (~1 liter). Finally, it is challenging to compare and assimilate data between networks: periods of record are not identical and the time between measurement and dissemination to the public is long [*Robock et al.*, 2000].

[4] Data gathered via satellite remote sensing provides consistent measurements of soil moisture on a global scale, but these data also have their difficulties because they use short wavelengths that are sensitive to soil moisture at depths of only several mm. At the same time, errors are introduced because the pixel size of measurements is much larger (~10's km) than the scale over which soil moisture varies [*Njoku and Entekhabi*, 1996; *Njoku et al.*, 2003]. Sampling may be infrequent (e.g., several days) compared to timescales of fluctuations [*Teuling et al.*, 2006]. Vegetation and soil roughness complicate interpretation of the satellite signal. Satellite missions SMOS [*Kerr et al.*, 2000] and SMAP [*Entekhabi et al.*, 2008] will employ L-band radiometers to minimize these problems. For example, SMAP will yield soil moisture estimates every 3 days with a spatial footprint of approximately 10 km. Due to larger penetration depths, the L-band systems will allow retrievals of soil moisture up to 5-cm depth [*Entekhabi et al.*, 2008]. These new missions will require a global network of stations that provides comparable, *in situ* measurements of soil moisture for scaling the magnitude of remote sensing estimates and quantifying the spatial and temporal variability that exists at finer scales than the satellite resolution [*Krajewski et al.*, 2006].

[5] Here, we demonstrate that GPS receivers originally installed for geophysical and geodetic applications can also be used to estimate fluctuations in near surface soil moisture. This is possible because GPS receivers gather energy from ground reflections in addition to the direct signal that travels between the GPS satellite and receiving antenna. The characteristics of the reflected signal change as soil moisture, and therefore the dielectric constant of the ground, varies. GPS-derived estimates shown here represent an average soil moisture value over an area of ~300 m^2, a much larger and more useful scale than typical *in situ* measurements. Given this sensitivity to soil moisture, some of the more than 5000 GPS receivers operated around the world by geodesists and geophysicists could be used to provide near-real time estimates of soil moisture for hydrology, climate, and ecology studies. Like the SMOS and

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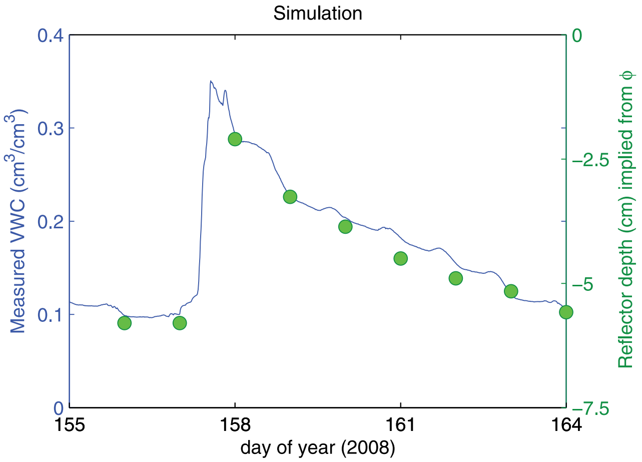

Figure 1. Multipath SNR was simulated for a constant antenna height (1.91 m), the L2 frequency, and satellite 29 observed at Marshall, Colorado. Multipath phase and amplitude were estimated (equation (1)) and ϕ was converted to an apparent reflector depth. A precipitation event VWC recorded at Marshall is also shown.

SMAP missions, the GPS signals are L-band (1.57542 and 1.22760 GHz). Thus, GPS receivers are an optimal *in situ* data source to combine with future satellite measurements.

2. Study Description

[6] For typical precise applications of GPS (e.g., plate boundary deformation, atmospheric water vapor, seismology), reflected signals are considered a source of error [*Braun et al.*, 2001; *Larson et al.*, 2007] rather than a useful signal. This phenomenon is referred to as "multipath," i.e.. a signal which travels more than one path (here, the direct path plus a reflection from the ground) before reception. We note that other researchers [*Garrison and Katzberg*, 1998; *Masters et al.*, 2000] have used GPS multipath for soil moisture studies. In those systems, a GPS receiver/antenna system specially designed to measure the reflected signal was used [*Katzberg et al.*, 2006]. In contrast, we examine the use of existing GPS instrumentation, designed to suppress multipath and installed on the Earth's surface for other purposes.

[7] The ground-based GPS site used here is located at Marshall, Colorado, ~10 meters from one of the 1100 GPS receivers operated by NSF's Earthscope network (http://www.earthscope.org). The vegetation type is short-grass steppe. We used the same equipment as Earthscope: a Trimble NetRS receiver with a choke-ring antenna (model TRM29659.00 with SCIT radome), with its phase center ~1.9 m above the ground (Figure S1 of the auxiliary material).[1] Unlike previous GPS soil moisture studies [*Katzberg et al.*, 2006], the gain pattern of this antenna favors signals above the horizon and suppresses reflections from below [see *Bilich et al.*, 2008, Figure 2].

[8] Although multipath affects all observations collected by a GPS receiver (pseudorange, carrier-phase, signal to noise ratio (SNR)) [*Ray and Cannon*, 2001], this study uses only the SNR. The SNR observation provides a low noise measure of carrier phase multipath that, unlike the carrier-phase and pseudorange observables, is independent of orbits, atmospheric delays, and clocks. SNR also has the advantage that it can be analyzed on a satellite-by-satellite basis, and the multipath characteristics can be related to physical properties of a particular part of the ground. In this study we use SNR data from only the six new Block IIR-M GPS satellites which broadcast L2 C/A signals, as Trimble NetRS receivers report high-quality SNR data for these signals. The new L2 signals show a 20 dB-Hz improvement in recorded SNR compared to the old L2 signals. Signals for these satellites reflect off the ground south of the antenna (Figure S2). The time of day at which an individual satellite senses a particular area advances by about 4 minutes/day due to the approximately sidereal ground repeat of GPS satellites [*Choi et al.*, 2004].

[9] Observed SNR values are the sum of the direct and multipath signal components. As this technique operates on the ground reflection component of SNR, the direct signal component must be removed. A wavelet transform [*Torrence and Compo*, 1998] is used to remove the very long-period direct signal power. Data above ~30 degrees elevation angle are discarded from the remaining SNR series as they contain no significant oscillations due to multipath [see *Bilich et al.*, 2008, Figure 3]. The final SNR series are converted from the native dB-Hz units into volts to represent the data on a linear scale.

[10] The equations describing GPS observations of reflections from the ground (or any horizontal planar reflector) have been known for many years [*Georgiadou and Kleusberg*, 1988]. For a known distance above the ground h, GPS wavelength λ, and elevation angle E, multipath reflections will have a frequency of $\frac{4\pi h}{\lambda}\cos E\frac{dE}{dt}$ [*Bilich et al.*, 2008; *Larson et al.*, 2008]. By using $\sin E$ as the independent variable, the oscillation frequency becomes $\frac{4\pi h}{\lambda}$, a constant and known quantity. This multipath frequency modulates the SNR, here expressed in terms of amplitude A and phase offset ϕ:

$$SNR = A\cos\left(\frac{4\pi h}{\lambda}\sin E + \phi\right) \tag{1}$$

Simulations (Figure 1) show that ϕ directly relates to the apparent reflection depth of the GPS signal. When the soil is wet, the apparent reflector is close to the surface; as it dries, the reflection depth is several cm deeper. *Larson et al.* [2008] compared multipath amplitude estimated via FFT to soil moisture variations from a model. In this study we use the multipath phase, as this parameter is sensitive to the very fine frequency changes expected from small changes in apparent reflector depth. Least squares estimation of the GPS SNR data (restricted to 10–30 degrees elevation angles) was used to find amplitude A and phase offset ϕ.

[11] In order to compare estimated ϕ with Volumetric Water Content (VWC), Campbell Scientific water content reflectometers (WCR) were installed at Marshall (Figure S3). These probes measure the time for the reflection of an electric pulse sent down two wave guides in the soil, which is related to the dielectric constant of the soil [*Topp et al.*, 1980]. The relationship between reflection time period and

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL036013.

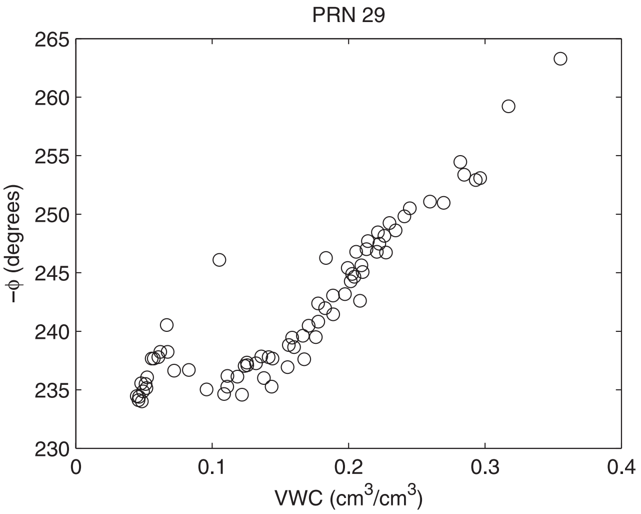

Figure 2. Estimated ϕ (for satellite 29) compared with VWC, as defined by the average of five water content reflectometers at depth 2.5 cm.

VWC was calibrated in the lab using soil from the site. The calibration is accurate to 1% moisture content, and was consistent with field samples collected on 3 separate days. Five probes were installed at 2.5 cm and five at 7.5 cm depth, to measure VWC in the 0–5 cm and 5–10 cm depth range [*Ferré et al.*, 1998].

[12] When comparing estimated ϕ and VWC measured by WCRs we see that there is a very simple relationship between the two measures (Figure 2). For this first comparison, a 2nd order polynomial is used to convert ϕ to VWC. Future work will concentrate on developing absolute retrieval algorithms that use the antenna gain pattern and known soil types and soil moisture profiles.

3. Results

[13] During the three-month observation interval, there were five distinct precipitation events (storm totals > 10 mm) and a week-long rainy interval beginning on day of year (DoY) 129 (Figure 3). The two events before DoY 115 had a mixture of rain and snow. The mean surface soil moisture measured between 0 and 5 cm, VWC_{0-5}, increased sharply during each precipitation event. VWC_{0-5} then decreased continuously until the next storm. Only after the storm on DoY 157 did the surface soil dry sufficiently to stabilize at an apparent residual water content of ~5%. Fluctuations of VWC from 5–10 cm depth were similar, although the increases following precipitation were not as large and the subsequent drying was slower.

[14] Each GPS data point in Figure 3 is an average over the ~45 minutes that a given satellite is reflecting from the area of ground under study. The correlation (r^2) between the individual converted satellite values and mean VWC_{0-5} time series is 0.91. The GPS data matches both the timing and amount of drying very closely for each of the five major wetting-drying cycles recorded by the WCR probes. For example, in both datasets, the drying following the DoY 109 storm is slower and lesser in magnitude than that observed following the DoY 157 event. The mean GPS signal is not as tightly correlated with the mean of VWC_{5-10} ($r^2 = 0.85$), as the deeper soil moisture decreases more slowly than that recorded by the GPS.

[15] The WCRs and GPS sample VWC at different scales, therefore the respective time series possess different levels of variability. Consistent with prior studies [*Famiglietti et al.*, 1999], the spatial variability of VWC_{0-5} is large (Figure S3). The range is typically 0.10 cm^3/cm^3, where much of the observed variability probably reflects actual VWC differences between probe locations, associated with soil texture or other factors. VWC variability approaches zero during the extended dry period in June. The variability among estimates derived from the six GPS satellites is less than from the WCRs, consistent with the larger area sensed by each satellite ground track (100 times larger than that of the WCR rods). The GPS values should represent an average of the heterogeneity that exists at the meter scale. Note that the GPS variability did not decrease during the extended dry period, when the variability of VWC_{0-5} was effectively zero. Therefore, we expect that the observed GPS variability is due not to soil moisture variance but to variations in antenna gain pattern (which affects received

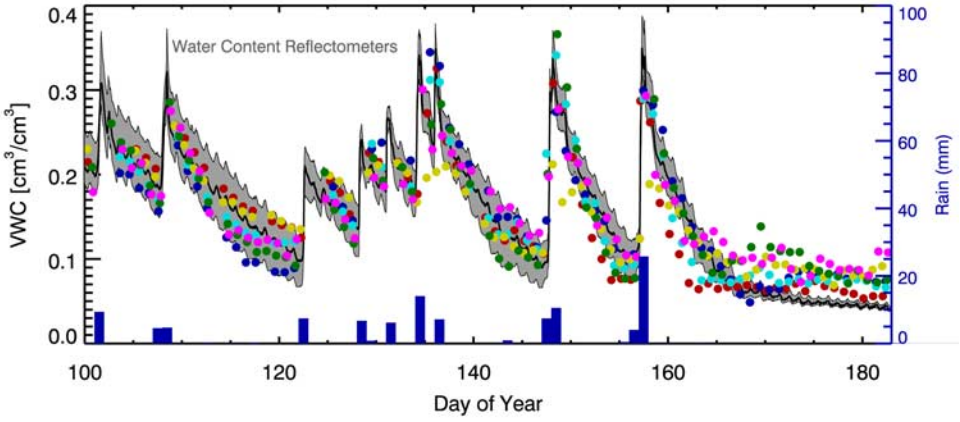

Figure 3. Variation in VWC from multiple GPS satellites (colors as in Figure S2) and water content reflectometers (WCR). The range of the five WCRs (Figure S3) is shown in grey and their mean is the black line. The daily precipitation totals are in blue. GPS measurements are only shown on days when there was no snow and the daily average temperature was above 3°C.

signal power and phase of the carrier wave) or heterogeneity in vegetation cover or surface roughness.

4. Discussion

[16] Continuously operating GPS networks represent a new data source for the hydrologic community. They are operated and archived by a variety of scientific and governmental agencies. GPS data are freely available on the internet, often in real-time, but always within 24 hours. Site installation (reconnaissance, permitting), operations, and maintenance costs are already supported. Ultimately the value of these existing GPS networks for hydrology will depend on local site conditions and spatial density. The basic requirement for GPS soil moisture sites is that the antenna be located above relatively flat natural surface and away from urban structures. This is often the case for geophysical monitoring networks such as Earthscope. Survey networks, however, are often deployed with antennas on buildings. Currently Japan, the US, and Europe have the largest GPS networks, producing publicly available data for more than 4000 receivers. In the US, GPS receiver spacing varies from 50–150 km depending on the region. As more GPS satellites are launched, azimuthal coverage at each station would be enlarged, increasing the sensed area to $\sim$1000 m^2.

[17] Additional work is needed to evaluate the GPS soil moisture technique. Although vegetation at Marshall does not block the GPS soil moisture signal, the effect of a range of vegetation structures needs to be evaluated, as is the case for all satellite-borne sensors. The impact of variations in GPS equipment (antennas and receivers) and retrieval algorithms also needs to be assessed. Finally, the technique should be tested for different soil types and surface roughness. There exists a large body of literature on retrieving soil moisture from L-band microwave radiometric observations [*Wigneron et al.*, 2003]. This will guide the development of new retrieval algorithms for the GPS soil moisture technique, including models that describe the dielectric properties of different types of soils and soil moisture profiles.

5. Conclusions

[18] A GPS receiver collocated with *in situ* soil moisture sensors shows excellent agreement in measuring near-surface volumetric water content variations. The technique described in this study could be applied to data from existing GPS networks, creating a global GPS soil moisture network. These soil moisture sensors would be valuable for hydrological studies, weather forecasting, and climate monitoring, as well as providing calibration/validation sites for soil moisture satellite missions planned for the next decade.

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