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Sensing vegetation growth with reflected GPS signals

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[1] Estimates of vegetation state are required for hydrometeorological modeling and validation of satellite estimates of land surface conditions. A linkage is described between vegetation growth and ground reflected multipath at GPS stations. Reflections are sensitive to conditions over a ~1000m^2 area, larger than typical *in situ* observations but smaller than space-based products. At two agricultural test sites, vegetation height and water content are inversely correlated with the magnitude of ground reflected multipath measured by geodetic-quality GPS stations. This relationship was tested further at Plate Boundary Observatory (PBO) network GPS sites, using Normalized Difference Vegetative Index (NDVI) to gauge vegetation status. NDVI is inversely correlated with the magnitude of multipath at nine sites located in grassland, shrubland and cropland. Multipath variations lag NDVI by approximately three weeks. Multipath statistics from existing sites are calculated daily and could be used to estimate biophysical properties in non-forested regions, which represent ~80% of land area. **Citation:** Small, E. E., K. M. Larson, and J. J. Braun (2010), Sensing vegetation growth with reflected GPS signals, *Geophys. Res. Lett.*, *37*, L12401, doi:10.1029/2010GL042951.

1. Introduction

[2] Measurements of vegetation state are required for climate and hydrologic modeling applications [*Sellers et al.*, 1986], validation of satellite estimates of land surface conditions [*Njoku and Entekhabi*, 1996], and testing of ecohydrological hypotheses [*Rodriguez-Iturbe*, 2000]. Remote sensing using microwave radar is one approach for documenting vegetation growth. Unlike optical methods, radar measurements are not hindered by cloud cover or time of day. In the microwave wavelengths, radar signals are sensitive to surface roughness and the water content of vegetation and surface soil [*Ulaby et al.*, 1986]. Therefore, the primary challenge when using microwave data for vegetation studies is removing the effects of soil moisture and surface roughness [*Brakke et al.*, 1981; *Prevot et al.*, 1993; *de Roo et al.*, 2001]. Vegetation mapping via Synthetic Aperture Radar (SAR), at L- and C-bands, is similarly complicated by the effects of soil moisture and surface roughness [*Hill et al.*, 1999; *Paloscia et al.*, 2004]. Although active microwave sensing can be used to estimate biophysical parameters, this type of data is not currently used to monitor changes in vegetation status at high frequencies (i.e., daily). Space-borne SAR is used for one-time surveys [*Shupe and Marsh*, 2004] or multi-temporal analyses with repeat times of months or longer [e.g., *Minchella et al.*, 2009].

[3] GPS satellites transmit L-band signals similar to those used in active microwave radar applications. GPS was first proposed as a remote sensing tool by *Martin-Neira* [1993]. In this configuration, reflected GPS signals (known as multipath) are tracked by a specially designed GPS receiver/antenna system flown on an aircraft or satellite. Two GPS antennas are used: one tracks the direct signal from the satellite and the other antenna faces the Earth to track the reflected signal [*Katzberg et al.*, 2006]. *Larson et al.* [2008a] proposed that geodetic-quality GPS instruments optimized to track the direct signal could also be used to measure reflected GPS signals: changes in the interference pattern between the direct and reflected signals are used as a remote sensing observation. Validation of this hypothesis was subsequently demonstrated for shallow soil moisture variations [*Larson et al.*, 2008b] and snow depth [*Larson et al.*, 2009] where multipath oscillations were characterized using the signal to noise (SNR) data recorded for the new GPS L2C signal [*Misra and Enge*, 2006]. In both test cases, the retrieval methods relied only on observing changes in frequency of the interference patterns caused by ground reflections and not on changes in amplitude.

[4] Here, we describe how GPS multipath amplitude variations can be used to estimate biophysical parameters. The dataset is from continuously operating GPS sites (Figure S1 of the auxiliary material) that were primarily installed for geophysical studies.[4] As vegetation grows, reflected GPS signals are reduced. This effect can directly be observed in the SNR observations, but it is also summarized by a noise statistic that is calculated daily by existing GPS networks. We first examine the effect of vegetation on GPS reflections in two controlled experiments to isolate the vegetation signal. Then, we show how multipath data from existing GPS networks is correlated with well-studied vegetation indices such as NDVI.

2. Vegetation Effects on GPS Multipath: Field Experiment Results

[5] During the 2009 growing season, we recorded GPS data and measured vegetation height and water content at both a hay field and a corn field in Boulder County, Colorado. We selected these sites for two reasons. First, scheduled agricultural manipulations (planting, cutting, etc.) allowed us to isolate the effects of vegetation growth on GPS multipath. Second, plants with geometries like grasses and corn interact

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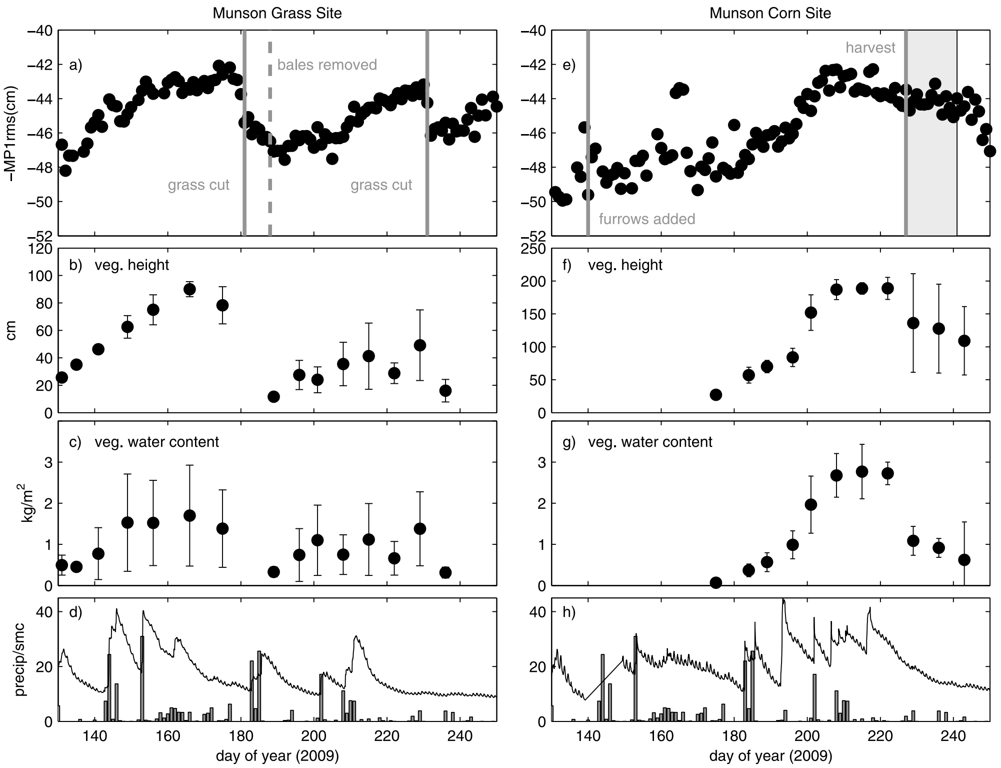

Figure 1. (a and e) MP1rms, (b and f) vegetation height, (c and g) vegetation water content, and (d and h) precipitation (mm) and volumetric soil moisture content measured by the average of 5 sensors at a depth of 2.5 cm. (left) Hay site and (right) corn site. The corn harvest—shown as the gray boxed region—lasted two weeks.

differently with microwave signals, due to the presence of vertical corn stalks [*Ulaby et al.*, 1986]. Therefore, we more fully test the utility of GPS for vegetation sensing by comparing how these distinct plant types influence multipath. The GPS receiver and antenna were chosen to correspond to those used by the Plate Boundary Observatory (PBO), a network of 1100 stations in the western U.S. We describe comparisons between additional vegetation types and GPS multipath below. Ancillary data were collected to quantify the importance of changes in soil surface roughness, soil moisture content, and precipitation. The environment around both sites was heterogeneous in terms of vegetation cover and engineered structures. Therefore, we restricted the GPS analyses so that they only included data from the azimuth directions whose footprints matched the azimuth directions of the hay field and the corn field.

[6] Vegetation was sampled weekly at both sites. At the hay site, we clipped and bagged all plant material in six 20 x 20 cm, randomly selected quadrats. Vegetation height was measured by estimating the 90th percentile height in each quadrat (i.e., outliers were ignored). At the corn site, we removed 6 corn plants by clipping them at the soil surface. The height of each plant was measured. All samples were weighed immediately after clipping, subsequently oven dried at 50° Celsius for 48 hours, and reweighed. Biomass and vegetation water content (VegWC, kg m^{-2}) were calculated, using the sampling area at the grass site and the stalk density at the corn site. There was substantial variability in VegWC at the hay site due to the inclusion of alfalfa plants (which had greater biomass) in roughly half of the selected quadrants.

[7] At the hay site, plant height and VegWC both increased from mid April until the initial harvest on day of year (DoY) 181 (Figure 1). The second growth period was characterized by smaller changes in grass height and VegWC. In contrast, alfalfa grew at a rate similar to the first period, resulting in greater variability in this portion of the hay height and VegWC records. The cornfield was devoid of vegetation (corn and weeds) until DoY 170, when the seedlings first became visible. Over the next 40 days, the corn grew to its full height of 200 cm, and remained at that height until the harvest began on DoY 230. The increase in VegWC is correlated with plant height. The harvest began on DoY 230 and continued for two weeks. During the harvest, paths were cleared for trucks and hand harvesting, leaving some stalks standing and other stalks bent over. As a result, there was more variability in corn height than earlier in the season. VegWC decreased by a factor of 3 after the start of the harvest, both because of the effects of harvesting and because irrigation was stopped around DoY 215 (Figure 1).

[8] Representative multipath oscillations at the two experimental sites are shown in Figure 2. At the hay site (Figure 2a), SNR data are shown before and after the field was mowed and baled (DoY 231 and 232). As expected, there is a clear change in amplitude of the SNR data for these two days. At low elevation angles, where the GPS footprint is largest, the SNR multipath amplitude is 55% greater after mowing than it was with vegetation. The effect of vegetation on the reflected signal is consistent with models of L-band signal propagation [*Ulaby et al.*, 1986] and experimental data [*Katzberg et al.*, 2006].

[9] Vegetation effects in GPS data can also be clearly seen at the corn site (Figure 2b), even though the scattering

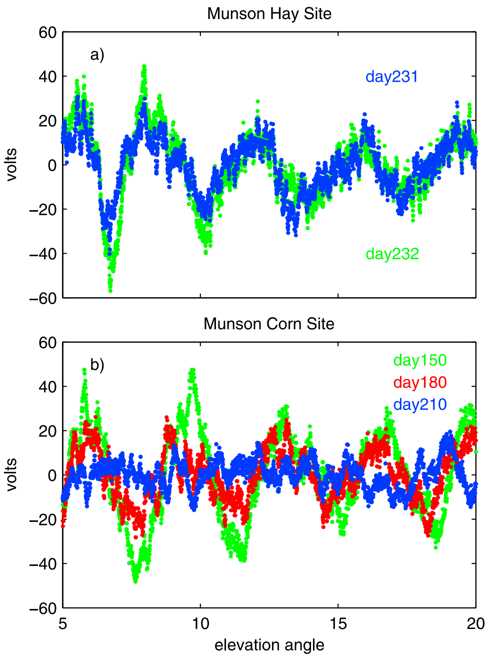

Figure 2. (a) SNR data for hay field before (day 231) and after (day 232) the field was mowed; (b) SNR data for no corn (day 150), 50 cm corn height (day 180), 2 m corn height (day 210). In addition to the effects of vegetation highlighted here, multipath amplitude decreases as the satellite rises because of the antenna gain pattern.

properties of corn are more complicated than for grass [*Ulaby et al.*, 1986]. We show three days with different amounts of vegetation: (1) bare ground prior to seedlings emerging (DoY 150); (2) ~50 cm high corn plants (DoY 180); and (3) when the corn reached its greatest height and water content (DoY 210). The SNR oscillations on DoY 150 show a strong interference pattern caused by reflection off the ground. The amplitude of oscillations is roughly half that of the bare ground magnitude when the corn plants were 50 cm tall (DoY 180). On DoY 210, the ground reflections are gone.

[10] Multipath effects can also be observed in a GPS noise statistic, MP1rms. MP1 is a linear combination of L1 and L2 carrier phase data and L1 pseudorange data [*Estey and Meertens*, 1999], where 1 and 2 indicate the satellite transmit frequencies of 1.57542 and 1.22760 GHz, respectively. Carrier phase data are biased but very precise (mm-level) ranges between the GPS receiver and satellites. These are the data used for crustal deformation experiments. Pseudorange data are much noisier (tens of cm precision) but unbiased. Both carrier phase and pseudorange data are sensitive to the effects of the troposphere, ionosphere, satellite orbits, receiver position, and clocks. The MP1 combination removes all of these effects except for the carrier phase bias (which is a constant), leaving one systematic error term: pseudorange multipath (MP) on the L1 frequency. MP1 also includes a random error term (ε) that depends on correlator spacing, averaging interval, the power of the direct signal and on thermal noise generated in the receiver and antenna (see chapter 10 of *Misra and Enge* [2006] for more details). Random variations in ε can be reduced by averaging MP1 values for many satellites. There is also a geometric effect caused by local topographic variations [*Katzberg et al.*, 2006]. We specify MP1rms here because we are using the RMS of the MP1 observations after the mean of the complete MP1 time series is removed.

[11] At the hay site variations in MP1rms are well-correlated with both vegetation height and VegWC (Figures 1a–1c). MP1rms decreased during the first growth period and then increased sharply on the day of the harvest to within 2 cm of the pre-growing season value. The cut hay was left on the ground (unbaled) for roughly 1 week. During this interval, MP1rms increased slowly to the value observed during the pre-growth period. MP1rms decreased throughout the second growth period and increased sharply on the day of the second harvest. The effects of soil moisture on MP1rms are small: MP1rms changes by only 1 cm as soil moisture varies across its entire range, regardless of the stage of vegetation growth.

[12] The same strong correlation exists between MP1rms and corn growth (Figures 1e–1g). MP1rms decreased steadily between DoY 170 and 205 and then remained nearly constant until DoY 220, consistent with the records of corn height and VegWC. MP1rms increased slowly following the harvest, and then more abruptly when the corn stalks were cut on DoY250. The post-harvest MP1rms record is more consistent with corn height than VegWC, as the latter dropped by nearly a factor of three during this period.

[13] It is relatively straightforward to relate time series of SNR data to VegWC using accepted models of microwave signal propagation [e.g., *Ulaby et al.*, 1986; *Katzberg et al.*, 2006]. The correlation between fluctuations in MP1rms and biophysical properties is less clear because MP1rms is not directly related to signal power. Regardless, there are two reasons why MP1rms records may be preferable for sensing fluctuations in vegetation state, at least at the current time. First, L2C SNR signals are not currently tracked by many GPS networks; they will not be available at the PBO network until the summer of 2010. In contrast, multi-year time series of MP1rms are readily available from GPS archives. Secondly, for vegetation with complicated structure, specular ground reflections are effectively eliminated (Figure 2b), making it impossible to estimate amplitude changes from SNR data. In contrast, MP1rms strongly correlates with vegetation measures at the corn site even after the SNR data show little signal.

3. Comparison of MP1rms to NDVI

[14] The experiments at the two agriculture sites demonstrate that fluctuations in MP1rms are linked to vegetation growth. In this section, we examine whether MP1rms from existing PBO GPS sites is related to fluctuations in vegetation state. We selected nine sites, three each from areas categorized as grassland, cropland, and shrubland according to the IGBP land cover classification derived from the MODIS product MOD12Q1. Together, these three land cover types represent more than two thirds of the U.S. land area, and a similar amount globally [*Loveland et al.*, 2000]. Therefore, our results are relevant for the most common vegetation types on earth, not just hay and corn as demonstrated by our agriculture experiments. We focus on the PBO network because it uses high-quality, standardized GPS instrumentation at each site, site conditions are well-documented, and the data are freely available.

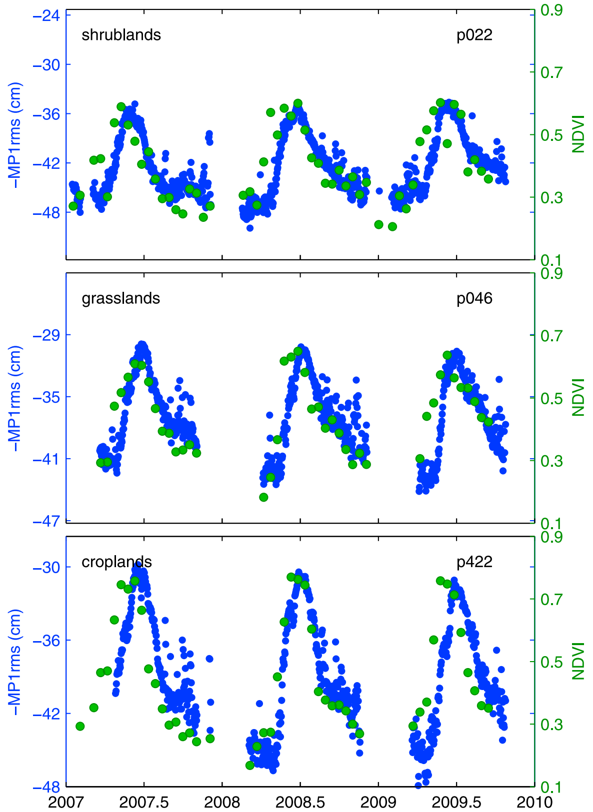

Figure 3. Comparison of MP1rms and NDVI for three land cover classifications: shrublands (P022), grasslands (P046), and croplands (P422). The NDVI time series (values less than 0.1) were used to screen times when snow was present. Since these NDVI data are available every 16 days and MP1rms every day, some of the MP1rms data shown are still corrupted by snow effects. Additional comparisons are shown in Figure S2.

[15] Since there are no direct measurements of vegetation water content or height at PBO sites, we compare the MP1rms records to Normalized Difference Vegetation Index (NDVI) time series. The NDVI data were from the 16-day MODIS product, extracted from the area surrounding the selected PBO sites. We did not anticipate an exact correlation between the two time series. NDVI is a measure of photosynthetically active radiation absorbed by plants [*Myneni et al.*, 1995], and therefore varies with measures such as leaf area index or productivity [*Paruelo et al.*, 1997]. In contrast, we expect that MP1rms is sensitive to the total amount of vegetation in the area surrounding the GPS antenna, regardless of the concentration of chlorophyll in the biomass. Any correlation between MP1rms and photosynthetic activity is not causal, but should only exist via linkages between biomass or vegetation water content and photosynthetic activity.

[16] MP1rms varies with the seasonal cycle of photosynthetic activity, as indicated by NDVI, at each of the PBO sites (Figures 3 and S2). These variations are consistent with the results from the agriculture experiments: as vegetation becomes increasingly green (higher NDVI) and presumably grows, MP1rms decreases. More vegetation enhances diffuse scattering and absorption, thereby reducing the coherence and strength of the multipath reflections. The opposite happens at the end of the growing season once the vegetation begins to senesce: NDVI decreases and MP1rms increases.

[17] Although correlations between NDVI and MP1rms are strong, the MP1rms fluctuations are clearly lagged. At five of the six grass and cropland sites, the strongest correlation exists at a lag of 3 weeks, with one having a stronger correlation with a lag of two weeks. Once lag effects are considered, the r^2 values are substantially higher (>0.8) at the grassland and cropland sites. A lag also exists at the shrub sites, but both the length of the lag and the increase in r^2 are not as consistent. Our lag analysis is only approximate because the NDVI data represents a 16-day window. The several week lag between NDVI and MP1rms is consistent with our conceptual model for how vegetation impacts MP1rms. The greening of leaves and increase in photosynthetic activity yields higher NDVI. The effect on MP1rms is only apparent after the increased photosynthetic activity yields additional plant growth, including components of the total biomass that are lower in chlorophyll than leaves.

4. Conclusions

[18] We have described a new method to estimate vegetation growth using GPS multipath. This method provides a unique estimate of vegetation water content or height: the data are representative of a well-defined footprint at an intermediate scale (1000 m^2) that is larger than *in situ* observations (e.g., from clipping or point counts) but smaller than space-based remotely sensed products. The footprint is similar to that derived from instruments mounted on planes, although these are usually single surveys or have long repeat times. The GPS data are available on a daily basis from networks of existing GPS sites, and therefore are particularly useful for validation of remote sensing products and initialization and parameterization of hydrometeorological models.

[19] One limitation of using GPS multipath for vegetation sensing is that this method is not practical in forested regions, which cover ~20% of the Earth's terrestrial surface [*Loveland et al.*, 2000]. GPS sites are rarely located in forests because trees block the direct GPS signal which degrades scientific positioning products. Our results show that GPS multipath is sensitive to plant growth in vegetation types that together cover a majority of the Earth's land surface, including cropland, grassland and shrubland. These are environments where optical remote sensing data is complicated by soil reflection [*Huete*, 1988], so the information provided by microwave remote sensing is particularly useful.

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