GPS GROUND NETWORKS FOR WATER CYCLE SENSING

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ABSTRACT

Tens of thousands of high-precision GPS receivers are operating around the world. With very few exceptions, the purpose of these receivers is to measure position. However, it is now known that GPS signals that reflect off nearby land surfaces and collected by these receivers can be used to measure shallow soil moisture variations, snow depth, and vegetation water content. These terrestrial water cycle products are distinctive in that they can be derived using widely-available GPS instruments. A water cycle portal created from data collected by a large GPS network in the western United States, the EarthScope Plate Boundary Observatory, is now available. It is updated daily at http://xenon.colorado.edu/portal. These data can be used for climate studies and satellite validation.

Index Terms— GPS, reflections, multipath, soil moisture, snow, vegetation water content

1. INTRODUCTION

Since first proposed by Martin-Neira [1] in 1993, reflected GPS (or more generally GNSS) signals have been exploited to measure water levels, soil moisture, snow depth, and vegetation parameters [2-5]. Typically these measurements are made with equipment designed to retrieve the reflected signal. At the same time that remote sensing engineers were developing instruments to measure GPS reflections, the geodetic community has been working with the opposite goal, to understand and eliminate reflection effects from their GPS data [6-7]. This goal has primarily been accomplished by careful receiver/antenna design by instrument manufacturers. Removing reflection effects through analysis software has been a much more challenging endeavor; it is rarely done except for high-rate positioning applications [8]. Although geodetic instruments are nominally designed to suppress reflections, it has recently been shown that reflection effects are still strong enough that geodetic GPS data can be used to accurately measure soil moisture, snow depth, and vegetation water content [9-11]. The footprint of this GPS method is ~1000 m^2. A recent demonstration project to measure these water cycle parameters with a large GPS network in the western United States is highlighted here. Based on data from the EarthScope Plate Boundary Observatory (PBO), it is called the PBO H_2O project

2. GPS NETWORKS AND MULTIPATH

It is well known that geodetic-quality GPS receivers record dual-frequency carrier phase and pseudorange observations. These data are routinely used by geodesists and surveyors to compute accurate positions. Figure 1 shows a typical geodetic-quality instrument operated in the western United States by PBO. Because this site is being used to measure plate motions and other small ground motions, a drill-braced monument is used to strongly anchor the GPS antenna to bedrock. The antenna is protected from the elements by the hemispherical dome. All sites in PBO operate continuously with default tracking set to 15 seconds, although many sites now also operate at 1 second. Nearly all sites telemeter data every day, with a large subset of sites transmitting data in real-time or in hourly batches.

Figure 1. Geodetic-quality GPS site located near Randolph, Utah. It is operated by UNAVCO for the EarthScope Plate Boundary Observatory. Solar panels and batteries are used to power the GPS receiver, which is stored in the white equipment box shown in the background.

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Geodetic-quality GPS receivers also generate signal to noise ratio (SNR) data on both frequencies. All three observables (carrier phase, pseudorange, and SNR) are compiled and made available via the internet to the surveying/geodetic community in an ascii format. Analysts use the carrier phase data, precise orbits, clocks, and atmospheric models to compute the positions used for crustal deformation models. These precise positions are known to be corrupted to some extent by the effects of signal reflections, or multipath. However, there is no standard geodetic model to remove these reflection effects.

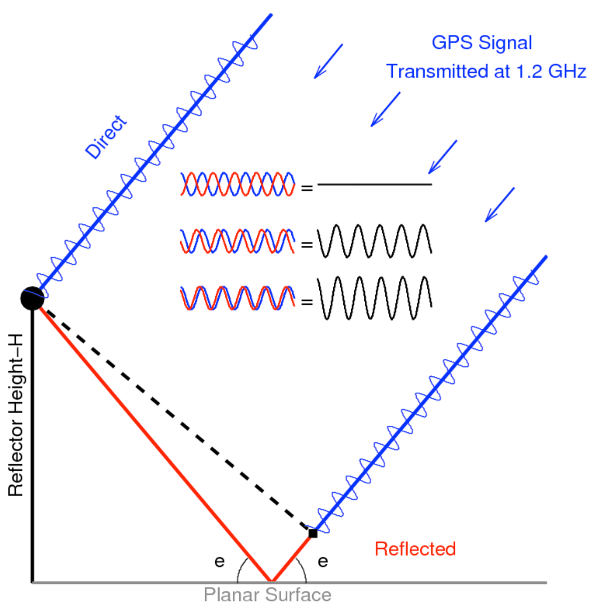

Figure 2. Geometry associated with reflected GPS signals. Reflected signals (red) interfere with direct signals (blue), generating an interference pattern (inset). The antenna is defined to be a distance H from the reflecting surface and the satellite elevation angle is shown as the parameter e.

The geometry for reflection effects at a standard GPS site is shown in Figure 2. The GPS antenna receives both direct and reflected signals; the direct signal is much stronger than the reflected signal. The latter travels an additional distance, which leads to the generation of an interference pattern in the SNR data; sample interference patterns are shown in the inset. For a horizontal planar surface the frequency of this interference pattern is directly related to the GPS transmission frequency and the height of the GPS antenna phase center above the reflecting surface. The amplitude of the interference pattern depends on the surface reflection coefficients and the transmit/receive antenna gain patterns [12].

The observed SNR interference pattern can be related through electrodynamic models to three key water cycle parameters: snow depth, soil moisture, and vegetation water content. Snow depth is linearly related to SNR frequency [10,13]. Near-surface soil moisture variations produce small changes in SNR phase offset [9,14]. Finally, increases in vegetation water content cause decreases in SNR amplitudes [11,15].

3. RESULTS

There are ~1100 GPS sites in the PBO network. The location of these sites is shown in Figures 3 and 4. The location of the sites is driven by geophysical considerations, i.e. half of the receivers are deployed in California to measure fault motion. Clusters of instruments are also deployed near volcanoes. For a variety of reasons, water cycle products are not created for each site. Currently ~410 GPS sites are used, with a breakdown of 100, 155, and 350 sites for the soil moisture, snow depth, and vegetation water content time series, respectively. These data are available at a public website, http://xenon.colorado.edu/portal. To put the GPS water cycle data into context, information about each site (landcover classification, snow and rain model output) and daily NLDAS (North American Land Data Assimilation System) precipitation and temperature data are also provided on the data portal. Because snow water equivalent (SWE) is a more useful measurement for water managers and climate scientists than snow depth, SWE data are created using nearby snow density sensors [16].

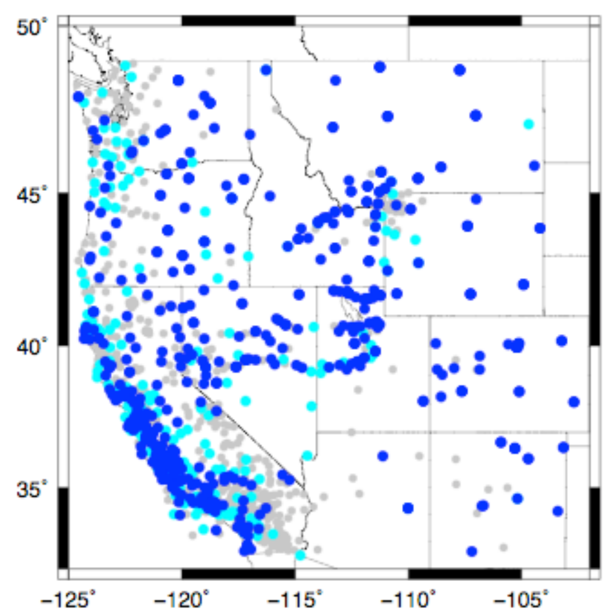

Figure 3. GPS sites operated by the Plate Boundary Observatory are shown by the circles. Blue indicates the sites currently used for water cycle products; products for sites with cyan circles will be available in fall 2014.

Figures 5-8 provide examples from the PBO H_2O database. In Figure 5 GPS vegetation products for a site in eastern Wyoming are compared with NDVI (normalized difference vegetation index). The GPS products are computed daily; here the 16-day NDVI products are shown. Because GPS is a L-band system, the reflections are most sensitive to variations in vegetation water content. NDVI is an optical measurement system and thus is most sensitive to the color of the vegetation; this strongly correlates with chlorophyll production. There is good correspondence at this site between the GPS and NDVI vegetation measures with a correlation of 0.74. They both show a dramatic response to the 2012 drought in eastern Wyoming. The GPS and NDVI time series also show a double peak in 2009.

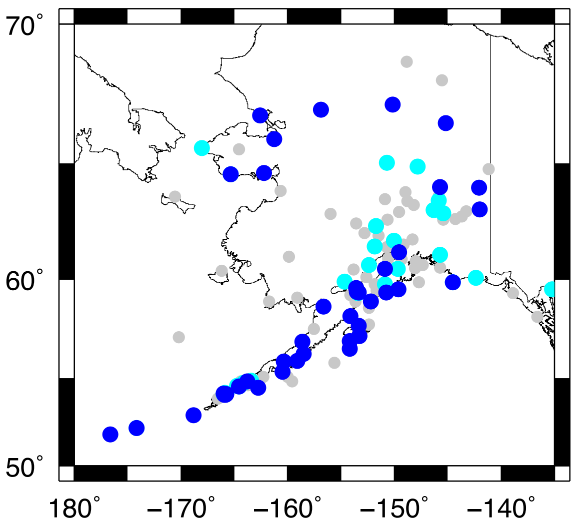

Figure 4. PBO sites in Alaska; see legend for Figure 3.

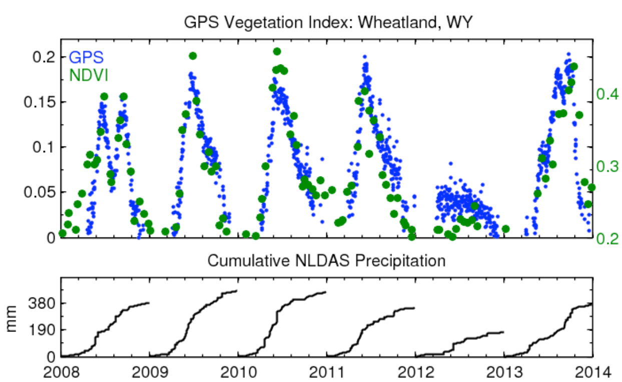

Figure 5. GPS vegetation index (left axis and blue circles) compared with NDVI (right axis and green circles). Cumulative precipitation derived from NLDAS is shown in black.

The agreement between the GPS vegetation index and NDVI is quite different in California PBO sites. Figure 6 shows GPS/NDVI data for a site in central California. Here the NDVI show a significantly longer growing season and earlier onset than the GPS data [17]. Furthermore, the GPS data in 2013 show a marked response to the drought conditions, while the NDVI data still show significant greenup.

Figure 7 shows three years of snow depth data from a GPS site in southern Idaho. There are significant variations in the amount and timing of snow. For example, the 2013 water year reached a meter of snow by December, whereas similar values of snow depth were only reached in March in 2012. Although not shown here, snow water equivalent measurements are also made available for the GPS sites, using modeled density values derived from the U.S. SNOTEL network.

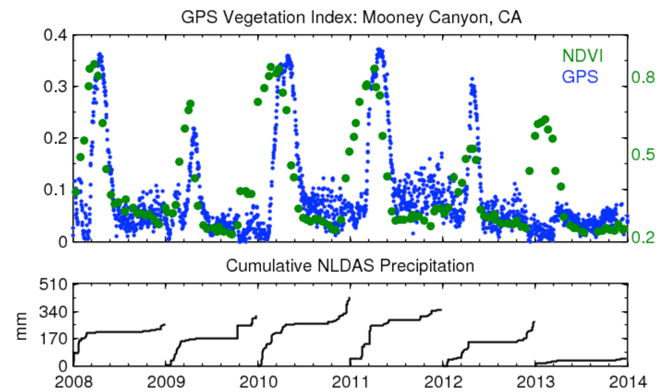

Figure 6. GPS vegetation index (left axis and blue circles) compared with NDVI (right axis and green circles). Cumulative precipitation derived from NLDAS is shown in black.

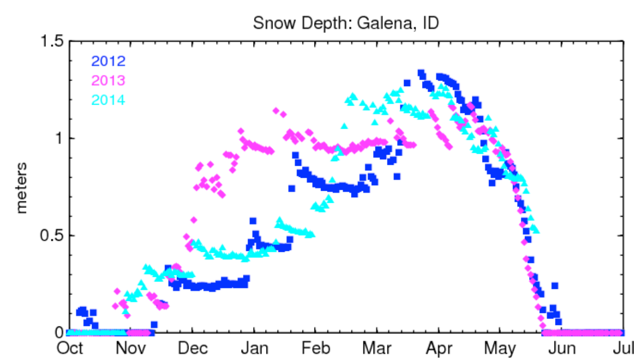

Figure 7. Snow depth measured at GPS site near Galena, Idaho for three water years. For clarity, error bars are not shown, but on average are 4 cm.

Finally, GPS-based volumetric soil moisture data are shown for a site in northern California in Figure 8. The GPS technique is primarily sensitive to the top 5 cm of soil, and thus has a strong correlation with precipitation events. Although currently the PBO H_2O portal only delivers daily products, the GPS technique can easily be used to derive subdaily products. There is a tradeoff however in the precision of those subdaily estimates.

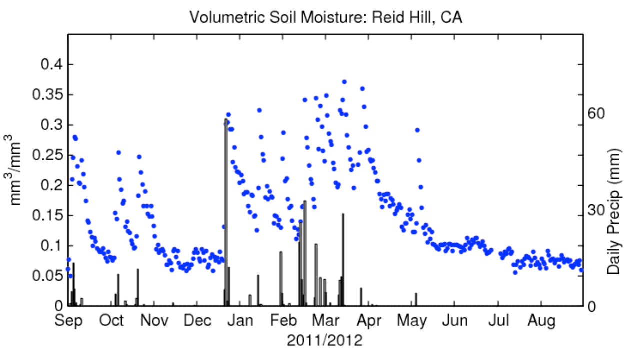

Figure 8. Volumetric soil moisture estimated at a PBO site in Northern California. Daily precipitation data come from NLDAS.

4. CONCLUSIONS

It is clear that reflected GPS (and more generally GNSS) signals have great potential for environmental sensing [18]. In addition to ground-based applications cited in the introduction, there are many efforts to use the method in space [19-21]. Geodetic GPS/GNSS receivers, such as those highlighted here, can also play an important role in environmental sensing by providing relatively local-scale measurements of soil moisture, snow depth, and vegetation water content. They can be used directly by climate scientists and water managers or as validation measurements for satellite missions. It has also been shown recently that you can accurately measure tides with geodetic GPS receivers if they are located close enough to the ocean [22]. The intrinsic value of all these new GPS reflection products is that the permanent GPS instruments can be simultaneously used by multiple communities: geophysicists monitoring volcanoes, surveyors measuring land boundaries, and polar scientists using base stations. Increasing the number of stakeholders for any scientific network significantly increases the likelihood that there will be support for long-term maintenance.

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