Environmental Sensing

A Revolution in GNSS Applications

KRISTINE M. LARSON
DEPARTMENT OF AEROSPACE ENGINEERING
SCIENCES, UNIVERSITY OF COLORADO

JOHN J. BRAUN
COSMIC, UNIVERSITY CORPORATION
FOR ATMOSPHERIC RESEARCH

ERIC E. SMALL
GEOLOGICAL SCIENCES, UNIV. COLORADO

VALERY U. ZAVOROTNY
EARTH SYSTEM RESEARCH LAB/NOAA

Increasingly sophisticated uses of GNSS observables have led to a new era in remote sensing. A team of researchers describe the results of the applications of interferometric reflectometry to measure snow depth, vegetation water content, and soil moisture.

In the past 20 years GPS has simultaneously revolutionized both our modern infrastructure (by providing real-time navigation, mapping, and timing support) and our geodetic/surveying capabilities (by providing millimeter/centimeter-level positioning). At this point, most of the GNSS innovations we expect to see in the next decade will come from calculating positions more accurately and faster, while expanding from GPS to use of all available GNSS signals.

Twenty years ago, in an article in *ESA Journal* (see Additional Resources section near the end of this article) Manual Martin-Neira presented a new application for GNSS. Instead of processing the direct GNSS signals for positioning, timing, and atmospheric studies, Martin-Neira suggested employing reflected GNSS signals as the measurement. The first GNSS reflection experiments were focused on altimetry, ocean winds, and soil moisture; later researchers evaluated GNSS reflectometry for sensing snow/ice and measuring vegetation growth.

Each of these reflection studies used GNSS instruments specially designed to measure reflected signals. In contrast, geodesists and surveyors use GNSS instruments that we know are designed to suppress reflected signals (more commonly referred to as *multipath*). While these reflections are known to affect the accuracy of positions derived from these instruments, there is still no standardized approach that models (and eliminates) the effect of reflections.

Most PBO sites are operated with banks of batteries that are powered by solar panels, as shown at PBO site P422. Inset: PBO site P101 in Randolph, Utah, which is used to measure snow depth in the winter and vegetation/soil moisture in the spring, summer, and fall. UNAVCO photos

In principle, this would suggest that GNSS reflection research is irrelevant for the tens of thousands of geodetic-quality GNSS receivers currently in operation around the world. Certainly GNSS reflections were never considered as a potential source of soil moisture, snow depth, and vegetation data when the EarthScope Plate Boundary Observatory (PBO) <http://pbo.earthscope.org> was built in the western United States between 2005 and 2008.

Unexpectedly, we have shown that these environmental data can be retrieved from PBO data without any instrumentation beyond the existing GNSS data stream. We can do this because the multipath data turn the GNSS site into a quasi-interferometer. The distance between the antenna and the surface reflecting material derived from the interferometric effect will tell us whether the top of the surface has moved. This means we can use the data to measure snow depth by comparing it to data when there is no snow.

If the reflected signal travels through vegetation, the interferometer will show two effects: the primary reflection is caused by the top of the soil layer and secondarily, the amplitude of the reflected power will be smaller because it interacted with water in the vegetation. Changes in soil moisture cause the smallest changes to the interferometric effect. We can think of these as being caused by the signals being reflected by the surface soil layers having various wetness levels.

These new measurements of soil moisture, snow, and vegetation measurements (called the PBO H2O network) are needed both for climate studies and satellite validation. Water managers use the data to predict, and hopefully mitigate, hazards such as floods and droughts. These new GNSS environmental data fill a niche between existing satellite sensors (that have very large footprints) and other *in situ* sensors (which tend to have very small footprints).

This article describes how we have created an operational GNSS environmental sensing network. We will first describe the network itself, followed by an overview of how reflections manifest themselves in GNSS observations, and ending with examples of environmental signals we have measured using this network in the western United States.

The Plate Boundary Observatory and Reflections

Consisting of about 1,100 stations, PBO was built by UNAVCO <http://www.unavco.org> under a contract with the U.S. National Science Foundation with the scientific goal of studying

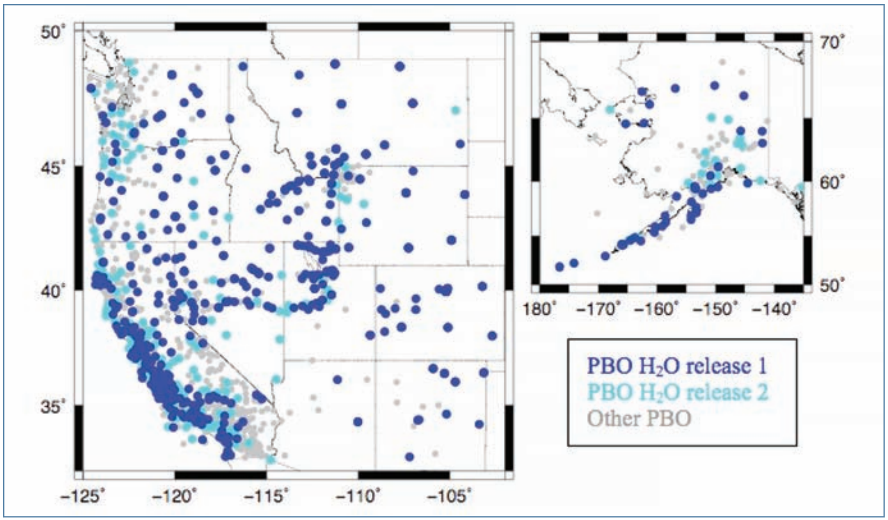

FIGURE 1 Circles represent locations of Plate Boundary Observatory (PBO) GNSS sites. Blue and cyan colored circles represent locations for PBO H2O product release versions 1 and 2.

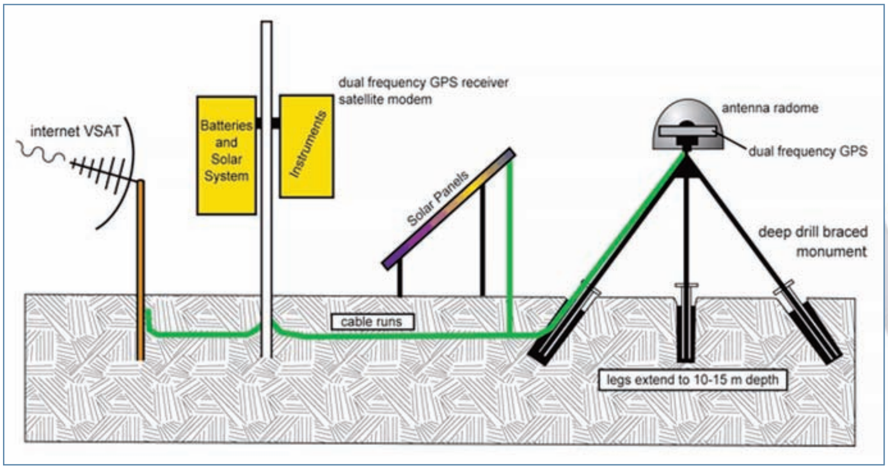

FIGURE 2 Schematic illustration of a typical PBO site. The radome protects the choke-ring antenna. Most sites are powered by solar panels. Except for some sites in Alaska, the data are telemetered at least daily. Credit: UNAVCO.

the motion of tectonic plates and the deformation of the North American continent. The locations of PBO sites (**Figure 1**) were chosen to address specific geophysical problems; thus, half of the GNSS sites are near fault zones in California. The east-west trending sites in Nevada and Utah are measuring motion in the Basin and Range province. Clusters of sites are also located near volcanoes (e.g. Yellowstone, Mammoth, Mount St. Helens, and the Aleutian arc).

After site locations were selected, the PBO project made special efforts to attach the GPS antenna to bedrock. Their reason for doing so was to ensure that the position (and velocity) information measured at each site would represent motion related to faults and volcanoes. For this reason, almost no PBO sites are located on buildings.

Figure 2 presents a schematic of a typical PBO site. A dual-frequency, choke-ring antenna is protected in an acrylic radome with a nearby equipment box housing the receiver and the telemetry hardware. The antenna's "drill-braced monument" is anchored to a depth of nearly three meters.

The standard PBO site operates a dual-frequency carrier phase receiver collecting GNSS signal data with a 15-second sampling interval; most also support 1-second sampling. With the exception of some sites in Alaska, the data are telemetered to the central UNAVCO facility in Boulder, Colorado, after midnight UTC each day; files of carrier phase and pseudorange data (called RINEX files) are produced by UNAVCO and posted online for public access soon after. Geophysicists are able to download the RINEX files for reprocessing, or they can download the frequently updated position time series in a standard terrestrial reference frame.

Velocity products that are used to study faults, earthquakes, and volcanoes, are also produced for the geophysical community. These PBO positioning products are based on very detailed models of the GNSS spacecraft, propagation delays, and Earth motions.

Although geophysicists and geodesists are well aware of the negative effects of reflected signals, there is still no standard model to remove reflection/multipath from these position/velocity products. This is partly because each GNSS site has unique reflection characteristics. Furthermore, many efforts to model multipath rely on stacking carrier phase residuals from least squares analyses. In principle these residuals could be used for environmental sensing; however, they can and will be influenced by mismodeled carrier phase data. Consequently, parameters in the least squares analysis could thus absorb or mask what was a real environmental change.

On the other hand, if one thinks about how best to measure *multipath reflections* rather than trying to *model multipath corrections* for carrier phase data, one might recast the problem to use signal power data. These are the analogous data to what is being used by the GNSS reflectometry community, which typically uses two receivers/antennas to separately measure the direct and reflected signal. The GNSS units used by geodesists and surveyors produces a single data stream and measurements that represent the interference of the direct and reflected signal. In the latter case, the antenna is not tuned to measure the reflected signal as it is with traditional GNSS reflectometry.

So, a key question arises: Are the signal power data collected by geo-


Inside

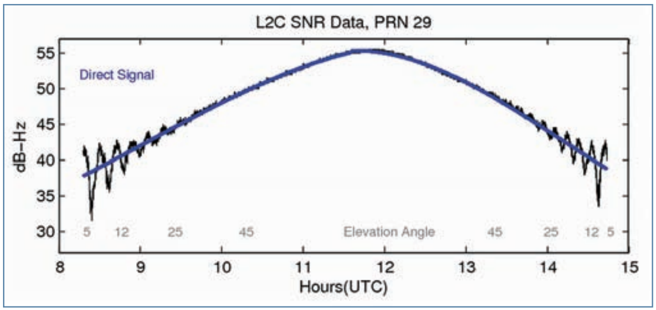

FIGURE 3 SNR data from the L2C signal collected at PBO site P041 for a single satellite track are shown in black. The smooth blue curve represents the direct signal. Elevation angles are shown in gray. The oscillations at low elevation angles are indicative of reflected signals/multipath effects.

detic/surveying GNSS units of sufficient quality to become inadvertent environmental reflectometers?

GNSS receivers generate carrier-to-noise density ratio data, which are stored in a RINEX file as signal-to-noise ratio (SNR) observables. **Figure 3** shows representative SNR data set collected by a geodetic-quality GNSS receiver. The direct signal has a simple polynomial shape, with lower SNR magnitudes at the rising and setting sections of the satellite track. These lower values primarily result from the antenna gain pattern. Superimposed on the direct signal are the reflected signals, which for horizontal planar reflectors manifest themselves as oscillations. Note particularly that little evidence of reflected signals appears above elevation angles of around 25 degrees. This is again due to the antenna gain pattern.

The transmitted GPS signal is right hand circularly polarized (RHCP). The reflection will have both RHCP and LHCP (left hand circularly polarized) components. As seen in **Figure 4**, the reflection coefficients are different for RHCP and LHCP, and depend on both the reflection surface and the satellite elevation angle.

The frequency of the reflected SNR signal is dominated by geometry, i.e., the extra path length traveled by the reflected signal, as seen in **Figure 5**. For a planar horizontal reflector, the frequency of the interference of the direct and reflected signal observed in SNR data is constant as a function of sine of the elevation angle. It is straightforward to extract this dominant frequency using a periodogram or estimate of the spectral density of the signal, a quantity that we call the *effective reflector height*.

If the effective reflector height changes, this means that the surface layer around the antenna changed. For example, an effective reflector height would change from 2.0 to 1.8 meters if it snowed 0.2 meters. To convert these effective reflector heights into an absolute measure of snow depth, we compare effective reflector heights estimated during the winter months with effective reflector heights determined when no snow is on the ground.

The amplitude of the reflection observed in the SNR data depends on the dielectric constant of the surface material — and, thus, very wet snow produces a different amplitude than very dry snow. Likewise, vegetation with high water content

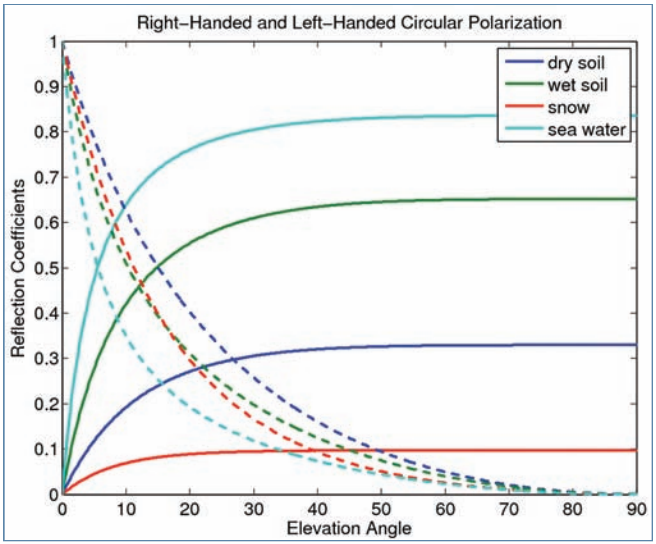

FIGURE 4 Reflection coefficients for a variety of natural surfaces at GPS frequencies and RHCP (dashed) and LHCP (solid) signals

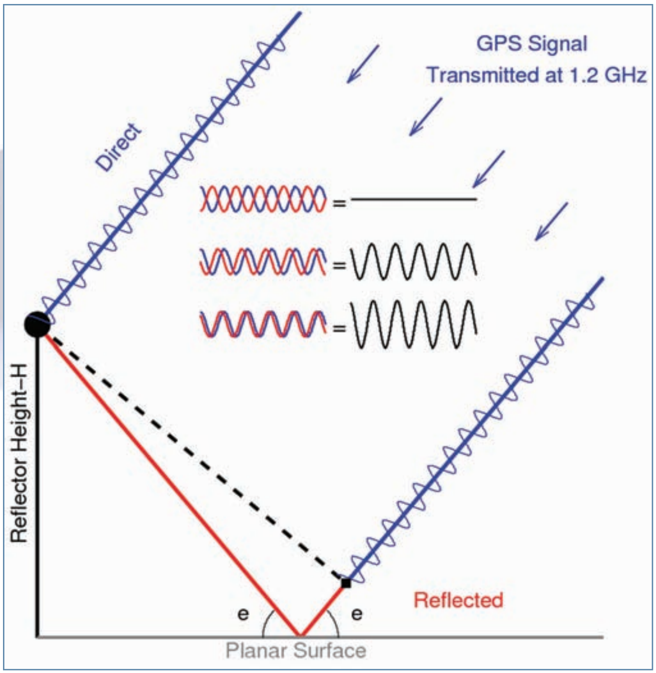

FIGURE 5 Schematic of multipath geometry for a horizontal planar surface. The direct L2 signal (shown in blue) is reflected at a planar surface and travels an additional distance (shown in red). Elevation angle is depicted by e. The GNSS unit measures the interference between the direct and reflected signals (examples of this interference are shown in the inset).

has much smaller SNR amplitudes than vegetation with very low water component. This is the principle used to define the vegetation statistic reported by PBO H_2O.

In order to define the snow depth, soil moisture, and vegetation water content measurements more rigorously we have developed forward models that contain information about the transmitted GPS signal, the gain pattern for the antenna used by PBO, and reflection coefficients for natural surfaces. These models have guided us in developing retrieval algorithms, which have been automated for PBO H_2O and published in the refereed literature. As part of this effort we have also conducted validation experiments where we measured soil moisture, snow depth, and vegetation water content *in situ*. These experiments have been invaluable in allowing us to improve our algorithms.

Results from PBO H_2O

The PBO H_2O initiative grew out of experiments conducted near Boulder, Colorado between 2007-2009. After several years of developing models and retrieval algorithms, the PBO H_2O network began operating in October 2012 with a data portal providing online access to users <http://xenon.colorado.edu/portal>. Figure 1 provides the location of the approximately 350 current sites along with about 200 new sites for which we plan to begin distributing data in the fall of 2014.

Data are downloaded from the central UNAVCO archive every evening, and new solutions for soil moisture, snow depth, and vegetation water content are posted each morning. To aid in quality control for our products, we also download other environmental datasets, such as hourly samples of modeled precipitation and temperature data from the North American Land Data Assimilation System and snow cover data from NASA's satellite-based Moderate Resolution Imaging Spectroradiometer (MODIS) project. These are useful for identifying outliers in our vegetation and soil moisture products. Photographs, Google maps, digital elevation maps, and climatology information are also provided for each site.

The following sections describe a few examples from each environmental dataset.

Snow. Our first snow depth measurements were made in 2009 at a flat mesa site south of Boulder. Although the snow depth retrievals were successful, we needed to demonstrate that the technique would work in more challenging environments. **Figure 6** shows the next snow site we tested. We chose a Niwot Ridge, Colorado, site because of its topographic variability (due to its location in a saddle at an elevation of about 3,500 meters), extreme cold, and very high winds. Power and Internet access was available from an existing scientific installation.

Five years later, the GPS snow depth time series from this site shows that the reflection method is robust, with very few data outages. Comparisons with *in situ* data (the pole in the photograph is measured roughly every two weeks) show that the method is also very accurate. Although the monument is three meters tall, as seen in the inset photograph in Figure 6, the antenna was almost buried in spring 2011. The latter was a banner snow year throughout the western United States, and a handful of PBO antennas were buried at snow peak.

Figure 7 shows snow levels measured at a PBO H_2O site near Island Park, Idaho. Unlike the station position time series generated for this site by geophysicists, which shows almost no variability, the snow changes at the site are quite

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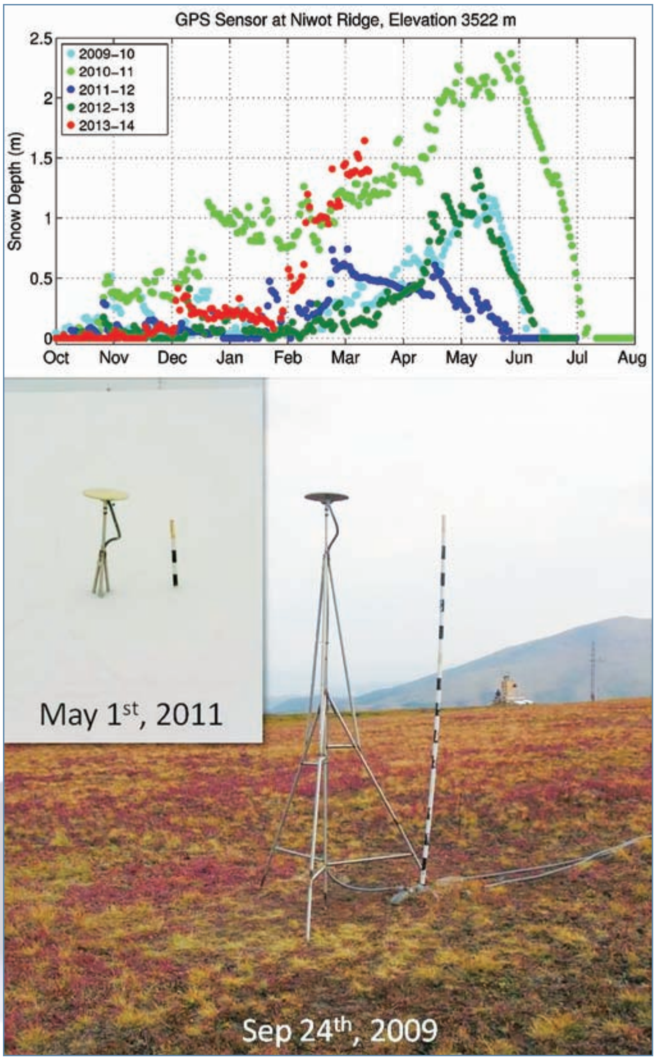


FIGURE 6 Top: five years of snow depth time series for the GPS site at Niwot Ridge, Colorado; bottom: Niwot Ridge GPS installation photographed in fall and early spring.

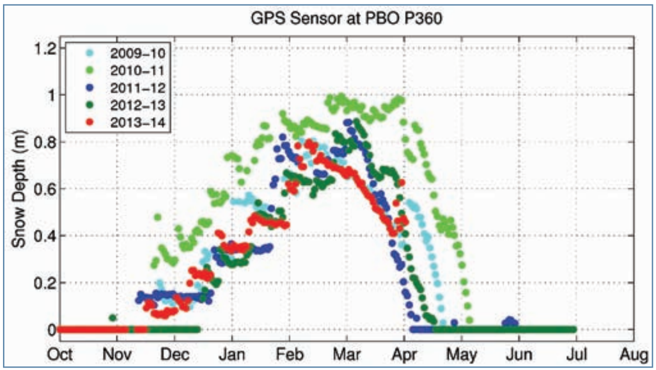


FIGURE 7 Five years of snow depth time series for the GPS site at P360 in southern Idaho.

dynamic. The first snowfall generally occurs at the same time each fall, but the peak snow amount is highly variable, as is the timing of snowmelt. The latter measurement is particularly important for predicting potential flooding. A video combining a series of photos of the station with corresponding weekly snow level plots may be viewed online at <http://

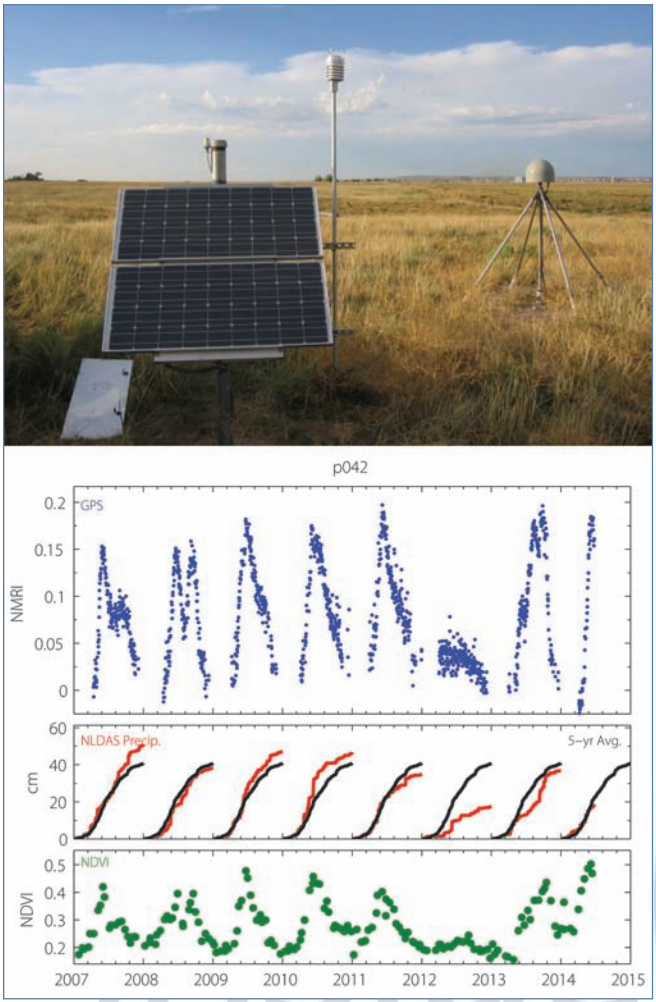
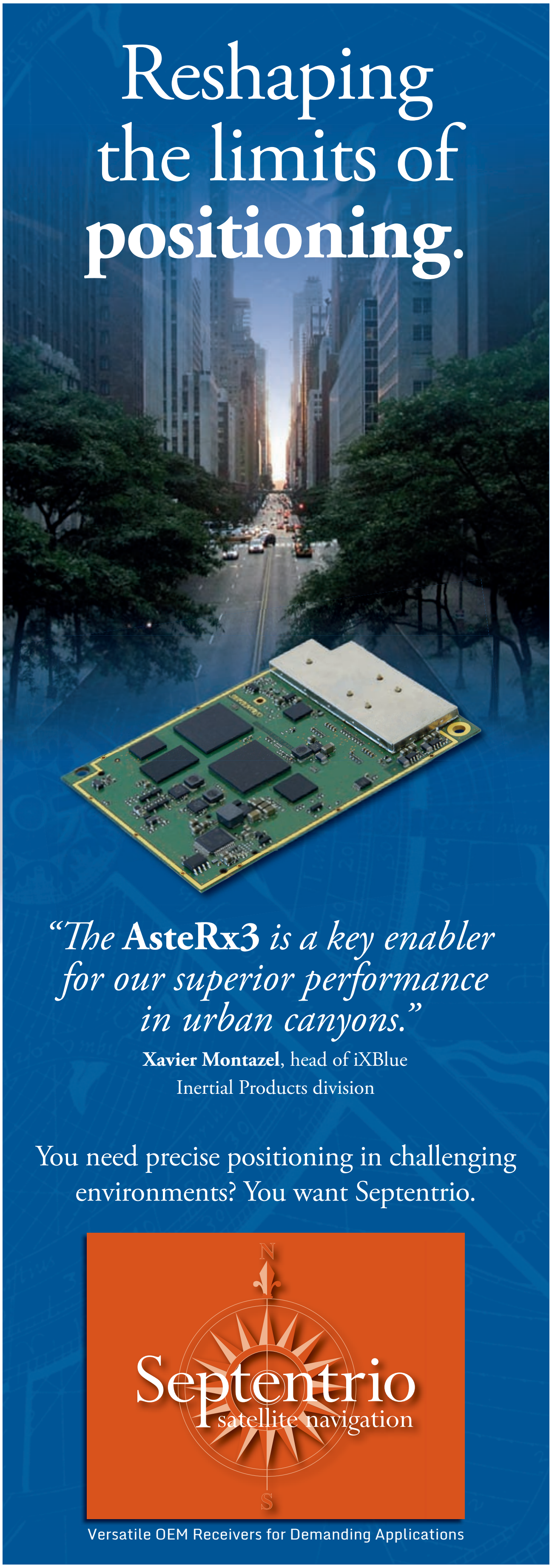


FIGURE 8 Top: GPS site at Wheatland, Wyoming; middle: GPS vegetation measurements (blue) compared with Normalized Difference Vegetation Index (green); bottom: cumulative precipitation from the North American Land Data Assimilation System (NLDAS). The GPS vegetation index is also called the Normalized Microwave Reflection Index (NMRI).

xenon.colorado.edu/spotlight/index.php?product=spotlight&station=p360>.

Vegetation. PBO H_2O vegetation measurements (NMRI, Normalized Microwave Reflection Index) are based on changes in the reflection amplitude, where values of zero represent the vegetation with the lowest water content. Figure 8 shows the vegetation data for a GNSS site in eastern Wyoming designated P042. This figure compares the NMRI vegetation water content estimates derived from GPS satellite data with the site's normalized difference vegetation index (NDVI). The latter are optical measurements — typically generated at 16-day intervals — using MODIS sensors that measure greenness, with each pixel representing a 250-square-meter footprint.

Greenness correlates strongly with photosynthesis production, and thus NDVI is commonly used to study vegetation growth. To provide some context, Figure 8 also shows modeled precipitation data (which is not directly measured at PBO sites). A close correlation appears between the GPS NMRI data and NDVI (correlation coefficient of 0.86). Particularly note the absence of greenness in 2012 and low GPS



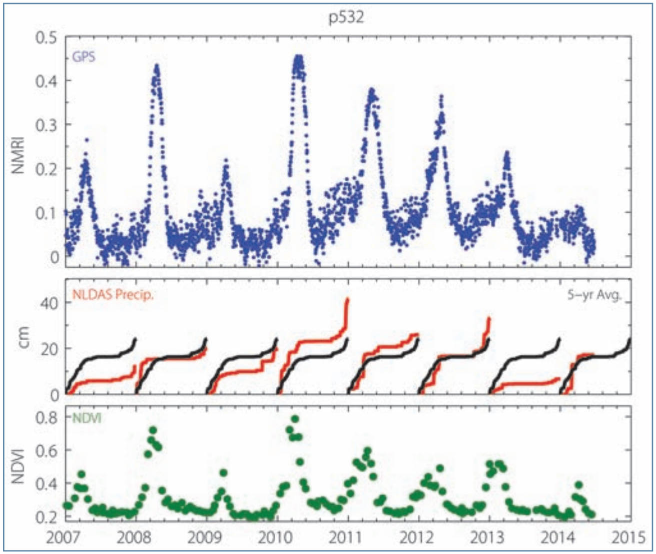


FIGURE 9 GPS vegetation growth index (NMRI) compared with NDVI and accumulated NLDAS precipitation at PBO site P532 located 50 miles northwest of Santa Barbara, California.

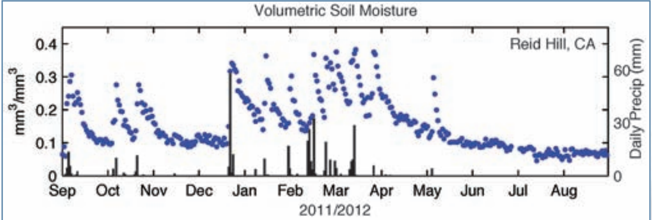


FIGURE 10 Daily measurements of volumetric soil moisture measured with GNSS (blue) and daily precipitation from NLDAS.

values during the 2012 drought. That year had low snowfall, a very hot spring, and very little rain. The P042 data record also shows a double growth peak in 2008. This phenomenon occurs when there are large gaps between rainfalls.

Similar sensitivity to vegetation growth is shown for California site P532 (**Figure 9**). Here both the GPS and NDVI records show strong sensitivity to the effects of drought, including 2014. Note that, although the rains in late February 2014 brought cumulative precipitation levels up to near the five-year average, vegetation water content as measured by NMRI has not recovered. Droughts effects in 2007 and 2009 are also clearly visible. A further note: the GPS vegetation data have a shorter "season length" than the NDVI data, with NDVI having a consistently longer growth season than the GPS measurement of vegetation water content.

Because GNSS reflections are sensitive to vegetation water content and NDVI is correlated to chlorophyll production, the combination of these measurements provides better constraints to phenologists studying the influence of climatic variations on periodic plant life cycles.

Soil Moisture. Soil moisture is the most challenging water cycle parameter to measure with GNSS receivers and faces some limitations. First, the reflection technique cannot measure soil moisture if there is snow on top of the soil. For PBO H_2O sites in the Rocky Mountains, we must remove data affected by snow. Second, soil covered by vegetation with very high water content (such as alfalfa) requires a more complex model of the reflections than we currently use.

Even with these restrictions, we have found many PBO sites that generate accurate soil moisture records. **Figure 10** shows such a record from a GNSS site near San Jose, California. Note that there is strong correlation between soil moisture changes and precipitation events, and then there is a "dry down." This is consistent with the behavior of a shallow (0-5 centimeter) soil moisture instrument. The sensing depth of the GNSS method is determined by its transmission frequency (L-band).

Although measurements of soil moisture are needed at depth as well as the surface, these GNSS data are particularly useful for satellite validation (ESA's SMOS mission and NASA's upcoming SMAP launch) because these sensors also operate at L-band.

Expanding PBO H2O to International GNSS Networks

Although the initial emphasis of our project was to use data from the PBO network, we must stress that no technical reason exists which prevents GNSS instruments operated by surveyors and transportation agencies from being used for environmental sensing. Both geophysicists and surveyors use dual-frequency carrier phase GNSS receivers — and, if properly configured, such receivers can generate SNR data that are

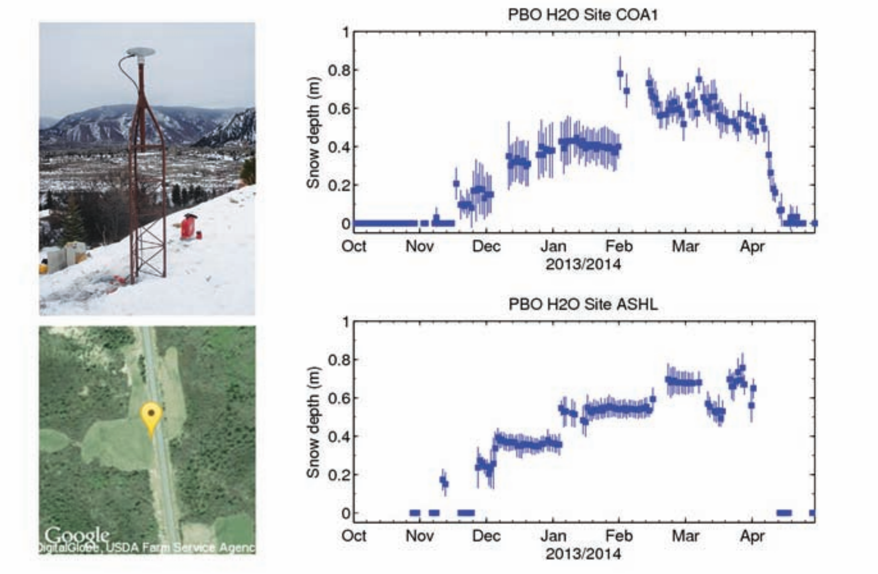


FIGURE 11 Top: GNSS site operated by the Mesa County Surveying Network located in Snowmass, Colorado; time series of snow depth for COA1 is shown for the 2014 water year; Bottom: the GNSS station operated near Ashland (ASHL) by the Minnesota Department of Transportation is located on the side of a road. The GNSS satellite tracks from the west of the monument can be used to measure snow depth.

suitable for reflectometry applications.

Configuration examples include requesting that the receiver track both legacy (L2 P-code) and new civilian (L2C) signals. The latter is preferred for reflection research because the code is public and the extracted signal power is higher. Second, some receivers produce SNR data rounded to the closest integer by default, which the station operator can easily change so that it generates a more precise SNR data stream.

To demonstrate that surveyor-operated GNSS sites can be used as snow sensors, we have recently partnered with two surveying organizations to expand PBO H_2O. **Figure 11** shows two examples from these efforts. In Colorado we have accessed data from the Mesa County Real-Time Virtual Reference Network <http://emap.mesacounty.us/GPS_Survey/GPS_Survey.htm>; the Minnesota data are distributed by the State Department of Transportation. Because the Minnesota sites tend to be located near highways, we used Google Earth images to window the data we used to measure show depth. For the Colorado sites, we used both photographs and Google Images. In both cases accuracy of the snow depth estimates is equivalent to that recovered from the PBO sites.

Can we measure soil moisture, snow depth, and vegetation at all GNSS sites? Unfortunately, the short answer is "no." Many GNSS sites have been installed on buildings and/or near parking lots, where reflections would be of little interest for the purposes described in this article. The locations of these sites also produce degraded positioning accuracy, but the degradation is often acceptable to the primary users of the data — geodesists, surveyors, and others.

The second limitation to using GNSS networks for environmental sensing has to do with data availability. While many organizations provide a RINEX file to national archives such as CORS, often these RINEX files do not include the SNR data. Furthermore, some archives degrade the RINEX files by eliminating observables and decimating the remaining data. This makes it difficult — and in some cases impossible — to extract useful environmental data from these. Although these issues constrain the use of data from some existing GNSS sites, we hope that results from PBO H_2O encourages future installations in locations that can measure positions and environmental changes simultaneously.

Final Remarks

Geodesists, geophysicists, and surveyors have all established large GNSS networks. Nearly all of them have open data policies and encourage broad usage of their data. The vast majority of GNSS data users focus on positioning, although the timing and atmospheric communities also value data from GNSS networks. Here we have shown how to further extend the value of

ground GNSS networks by describing how to routinely measure soil moisture, snow depth, and vegetation growth. These data are valuable both to scientists and water managers and a cost-effective use of existing infrastructure.

Acknowledgments

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Manufacturers

The standard PBO sites use NetRS GNSS receivers from **Trimble**, Sunnyvale, California, USA.

Additional Resources

GNSS-Reflectometry

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Authors

Kristine M. Larson received the B.A. degree in engineering sciences from Harvard University and the Ph.D. degree in geophysics from the Scripps Institution of Oceanography, University of California at San Diego. She was a member of the technical staff at the Jet Propulsion Lab from 1988–1990. Since 1990, she has been a professor in the Department of Aerospace Engineering Sciences, University of Colorado, Boulder. Her research interests are focused on developing new applications and techniques for GPS.

Eric E. Small received a B.A. degree in geological sciences from Williams College and the Ph.D. degree in earth sciences from the University of California at Santa Cruz. He is a professor in the Department of Geological Sciences, University of Colorado, Boulder. His research is focused on land surface hydrology.

John J. Braun received the B.A. degree in physics and mathematics from the University of Colorado, Boulder, and the Ph.D. degree from the Department of Aerospace Engineering Sciences, University of Colorado. He is a project scientist within the COSMIC program at the University Corporation for Atmospheric Research, Boulder. His research interests include developing new techniques and using GNSS observations to study the Earth and its environment, particularly the water cycle.

Valery U. Zavorotny received the M.Sc. degree in radio physics from Gorky State University, Gorky, Russia, and the Ph.D. degree in physics and mathematics from the Institute of Atmospheric Physics, USSR Academy of Sciences, Moscow. From 1971 to 1990, he was a research scientist with the Institute of Atmospheric Physics of the USSR Academy of Sciences, Moscow. From 1991–2000, he was a CIRES Research Associate in the Environmental Technology Laboratory of the National Oceanic and Atmospheric Administration (NOAA), Boulder, CO, and became a NOAA/ETL physicist in 2000. His research interests include theory of wave propagation through random media, wave scattering from rough surfaces, and ocean and land remote sensing applications. IG

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