GPS interferometric reflectometry: applications to surface soil moisture, snow depth, and vegetation water content in the western United States

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GPS interferometric reflectometry is a new environmental sensing technique that can be used to measure near-surface soil moisture, snow depth, and vegetation water content variations. The spatial scale of this technique, ~1000 m^2, is intermediate to that of other in situ sensors (<1 m^2) and satellites (>100 km^2). Soil moisture and snow depth retrievals have accuracies of 0.04 m^3/m^3 and 0.04 m, respectively. These accuracies are sufficient for many hydrologic applications. Fortuitously, GPS interferometric reflectometry can be used with consumer-grade off the shelf GPS instruments that are operated by the geodetic, geophysical, and surveying communities. This means that GPS data from thousands of sites are potentially available for environmental scientists seeking new in situ data for soil moisture, snow depth, and vegetation water content. The technique can be applied to data from existing archives or for new sites. Although the accuracy of the technique has only been evaluated for the GPS constellation, the technique can also be used for other navigation constellations such as GLONASS, Galileo, and Beidou.

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INTRODUCTION

In the past 20 years, GPS has revolutionized our daily lives by providing real-time navigation and mapping information in our cars and phones; GPS is also the *de facto* provider of timing information to the public.[1] So-called 'navigation users' of GPS rely primarily on the codes that are imprinted on the signals, which provide precision levels of ~5-m level for positioning.[1] A much smaller community of GPS users—'geodetic users'—take advantage of the carrier signal. These data are significantly more precise than the codes.[2] This segment of the GPS signal provides a precision of ~1 cm for positioning. This kind of precision is needed for surveyors and construction engineers.[2] In the geosciences, geodetic GPS is the primary method used to measure fault motions and plate tectonics.[3] In all of these geodetic applications, the carrier ranging measurements made by the GPS instruments are used with geodetic software to estimate position or relative position. The hallmarks of geodetic software are highly sophisticated models to predict and remove a variety of errors that influence the carrier ranging data, such as orbits for the different GPS satellites.[2] Both the GPS satellites and receivers have their own clocks, so the geodetic software must estimate these timing variations as well.[2] As predicted by Einstein, clock variability on the GPS satellites are affected by their orbital speed and the Earth's gravitational field. Some of these relativistic

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effects are compensated for by the GPS operators themselves, but the other relativistic corrections must be applied at the time the data are analyzed.[4] Finally, because the signals travel through the Earth's atmosphere, geodesists and surveyors must also remove the effects caused by ionized electrons (in the ionosphere), gases, and water vapor.[2]

As the cost of a geodetic GPS receiver dropped and the GPS constellation itself reached its design size of 24 satellites in 1993, usage and deployment of geodetic GPS equipment has dramatically increased.[5] These GPS units are fairly simple to operate, and data volumes are low enough that the data can now be easily telemetered in real-time in many regions of the world. Even in regions without advanced ground-based infrastructure, GPS data can be accessed using satellite telemetry. The locations of these continuously operating GPS (CGPS) sites with public data streams depend on a variety of factors. In seismically active regions of the western United States, most GPS sites were installed by geoscientists.[3] GPS networks in the eastern and central United States were primarily installed to support surveyors[6]; they are mostly operated by local state governments. In Japan, a dense national network (GEONET) simultaneously provides data for both surveyors and geoscientists.[7] Although access to data from these networks varies somewhat, those that were funded by taxpayers usually make the GPS data available to the public, with the number of public sites far in excess of 10,000.[5] Along with the expansion of CGPS networks, the GPS constellation itself has been improved in the past decade. Instead of the planned 24 satellites, the constellation now consists of 31 satellites; of this total, eighteen satellites have enhanced capabilities for both navigation and geodetic users.[1]

Although installed for positioning, data from CGPS sites can also be used to probe the ionosphere and troposphere.[8,9] As telemetry links for CGPS networks have improved, GPS data are increasingly being used for real-time applications, including weather prediction, tsunami warning, and earthquake early warning.[10–12] A more recent application of GPS—GPS interferometric reflectometry (GPS-IR)—is the focus of this overview.[13–15] As with atmospheric GPS applications, GPS-IR takes advantage of an error source (reflected signals or multipath) and turns it into a measurement for non-geodesists. Here the focus will be on measurements of soil moisture, snow depth, or vegetation water content that have been derived from data collected with geodetic GPS instruments. These measurements of soil moisture, snow depth, and vegetation water content are of value for both climate studies and satellite validation. Water managers need these kinds of data to predict, and hopefully mitigate, hazards such as floods and droughts. GPS-IR 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). That being said, the primary reason GPS-IR has such potential for environmental research is because it can be used with existing GPS instrumentation, thus providing data at very little cost. Of course, it is possible (although expensive) to install new soil moisture, snow depth, and vegetation networks, the added costs of maintaining these networks on a global basis would be immense. Ideally these quantities could be monitored by satellites, but this can be very difficult to do, the cost of satellite missions is also large, and satellite data are sometimes only available for short time spans. For climate studies, access to long data records is critical. The geodesists, surveyors, and geophysicists that operate CGPS networks also have an interest in long data records, which means both groups could benefit by sharing the data from their monitoring networks.

The goal of this short review article is to provide the reader with an understanding of how the GPS-IR technique works and to provide a summary of recent GPS-IR results derived from a CGPS network in the western United States. In the final section, there will be a discussion of the potential of GPS-IR for global CGPS networks.

GPS INTERFEROMETRIC REFLECTOMETRY

There are currently 31 GPS satellites and two primary GPS frequencies. These frequencies are in the L-band (~1.5 and 1.2 GHz, equivalent to ~19 and 24.4 cm), and are called L1 and L2. The satellites are distributed in six orbital planes, which are inclined 55 degrees with respect to the equator.[1,2] They have a nearly half-sidereal orbital period (11 h, 58 min). The practical effect of the GPS orbital period is that a satellite will appear to be in the same place in the sky every day, but shifted by ~4 min.[16] This means GPS has a repeating ground track; this is not a requirement, but will be helpful for implementing GPS-IR.

To understand how to change a GPS site into a GPS-IR sensor, one needs to understand the basic geometry associated with a reflected GPS signal, the characteristics of the transmitted signal, the receiving antenna, and the surface, and its footprint.

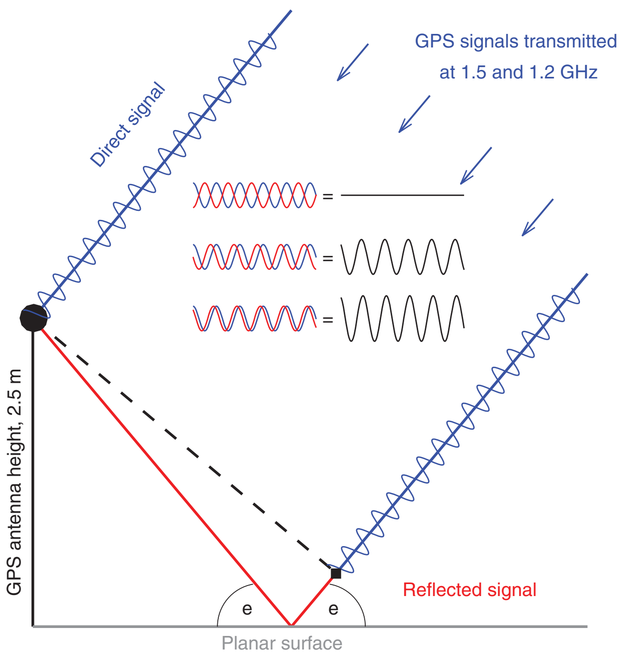

FIGURE 1 | Multipath geometry for a horizontal planar reflector. Satellite elevation angle is designated by the variable *e*. A GPS antenna measures the interference between the direct (blue) and reflected (red) signals. Examples of this interference are shown in the inset.

Geometry

The geometry for a simple (planar and horizontal) ground reflection is depicted in Figure 1. The incoming GPS signal is described by its elevation angle (e), which is the angle between the antenna-transmitter vector and a local horizontal vector. For the purpose of describing GPS-IR, the direct signal (shown in blue) travels along the straight line between the transmitted GPS satellite and the receiving antenna. One can think of the direct signal as a simple sine wave (on either L1 or L2) with a certain number of cycles. The corresponding reflected signal has traveled a further distance (shown in red) than the direct signal, and thus has more cycles. The antenna receives these two signals—the much stronger direct signal and a weaker reflected signal. The interference of these two signals is what causes 'multipath,' an error in geodetic applications,[17] but the useful signal for GPS-IR. The multipath signal constructively and destructively interferes with the direct signal as a GPS satellite rises or sets. One can characterize the expected interference pattern from a horizontal, planar ground reflection by a sine wave with a constant frequency (*SNR*). The latter depends on the height of the antenna's phase center above the reflecting surface (H) and the GPS wavelength, λ, where the dependence is on sine of elevation angle rather than time:

$$SNR = A(e)sin\left(4\pi H\lambda^{-1}sin(e) + \phi\right) \quad (1)$$

There is also an amplitude term (A) that depends on elevation angle, surface roughness, and the dielectric constant of the surface, and phase (ϕ). Antennas used by geodesists and surveyors are designed to suppress reflected signals. However, most of this efficiency comes for satellite elevation angles above 30 degrees. Below this threshold, it is straightforward to observe reflected signals if the reflecting surface is planar and relatively smooth. If you have specific information about the gains for your geodetic antenna, you can predict how the interference pattern will change depending on the reflecting surface's dielectric constant and roughness, along with H and e.[18]

Footprint

The GPS-IR footprint—also called the Fresnel zone—for an individual GPS satellite track is represented in Figure 2(a). The Fresnel zone is a narrow ellipse that depends on the antenna height H and elevation angle e. In the example shown, an antenna height of 1.8 m is used and the elevation angles plotted range from 7 to 25 degrees. As a satellite rises, the Fresnel zone becomes smaller and closer to the antenna. If the reflected signals from all GPS satellites can be used (here we show satellite tracks for a GPS-IR site in the western United States), the footprint for a single site would look like Figure 2(b) and have a footprint of ~1000 m^2. Note that the site footprint has a distinctive hole to the north, which is a consequence of the GPS satellite inclination of 55 degrees. There would be an equivalent hole to the south for a GPS site in the southern hemisphere. While many *in situ* sensors sample regions of ~0.01–5 m^2, the GPS-IR technique gives a much larger footprint, with a radius of ~20–30 m for typical GPS sites. Because GPS satellite orbits are well known, the footprint for any GPS-IR site can be predicted before an instrument is installed.[19]

GPS Signal-to-Noise Ratio Data

The effects of reflected signals are most easily quantified using an engineering measurement of signal power, called the signal-to-noise ratio (SNR). Typical time series of SNR data from a geodetic GPS receiver are shown in Figure 3(a) and (b). This particular antenna is ~2 m above a horizontal and planar soil surface. The slow change in SNR values from 35 to 45 dB-Hz is the direct signal effect resulting from the antenna design. The oscillations superimposed on the direct signal are caused by the reflected signals; this is the part of the signal used in GPS-IR. The SNR data are typically converted from their native logarithmic

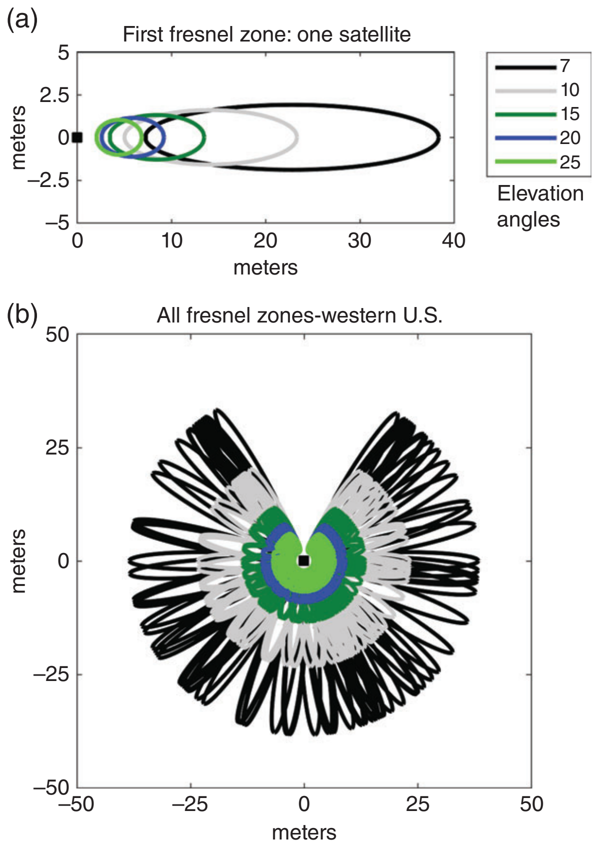

FIGURE 2 | (a) The first Fresnel zone for a single satellite track is depicted for satellite elevation angles of 7, 10, 15, 20, and 25 degrees and an antenna height of 1.8 m. (b) Map view for the GPS-IR footprint in the western United States for all transmitting GPS satellites. The location of the GPS antenna is shown as the black square.

units (dB-Hz) to a linear scale (volt/volt) and a low order polynomial is fit to data below an elevation angle of 30 degrees. The remaining SNR 'interferogram' is shown in Figure 3(c).

In principle we can extract reflected signals from both L1 and L2 SNR data (Figure 3(c)). In practice, it can be quite challenging. In this example, one can see that the L1 data from this particular PBO receiver appears to have more high frequency noise than the L2 data. This is clearer in Figure 3(d), where periodograms are computed from both the L1 and L2 SNR data. Both datasets show a peak at a reflector height of ~2 m, but the L2 peak is much larger than the L1 peak and L2 noise levels at other frequencies are much smaller. Nevertheless, multiple groups have reported being able to extract accurate soil moisture and snow depth products from both frequencies.[20–23]

Data Analysis

We extract three parameters from a SNR interferogram (Figure 3(c)). If we assume a constant frequency (i.e., given H in Eq. (1)), we can estimate amplitude A and phase ϕ using least squares estimation. It is this latter term that is highly corrected with volumetric water content in the top 5 cm of soil.[13,24] Using electromagnetic forward models, retrieval algorithms have been derived for both bare soil[25] and bare soil with vegetation canopies.[26] Secondly, we can use a periodogram to estimate the dominant frequency H—or reflector height (Figure 3(d)). If the reflector height changes, this indicates that the dominant reflection layer around the antenna changed. For example, there could be a 10 cm layer of snow on top of bare soil, which means the retrieved value of H will be 10 cm smaller.[19] The retrieved amplitude from either of these analyses (the least squares estimation or the periodogram) provides useful information about changes in vegetation water content. More details for vegetation products derived using GPS-IR are available in Ref 27.

RESULTS

Plate Boundary Observatory Water Initiative: PBO H_2O

At the time the GPS-IR technique was being developed and tested,[13–15] the U.S. National Science Foundation was building a large GPS network in the western United States. The scientific goals of the network were to better understand the mechanisms that deform the boundary zone between the Pacific and North American plates, and thus the effort was termed the Plate Boundary Observatory (PBO; Figure 4). While some of the sites are clustered near volcanoes, the vast majority of sites are located near fault zones in the western United States. In addition to the scientific targets, sites were chosen to accommodate land-use restrictions and access to telemetry. Each PBO site uses a geodetic GPS receiver and antenna. Most of the sites have their data telemetered once per day to a central archive, although a significant portion stream data in real-time or hourly. All PBO data are freely available to the public; many of these data are used by surveyors.

PBO H_2O is an initiative to translate PBO data streams into environmental products. PBO H_2O began in Fall 2012. Data are downloaded from the central PBO archive at the end of each UTC day (http://pbo.unavco.org) and environmental products are posted 12 h later at http://xenon.colorado.edu/portal. All the examples of water cycle products that will be shared in the next three sections are derived from the PBO H_2O project.

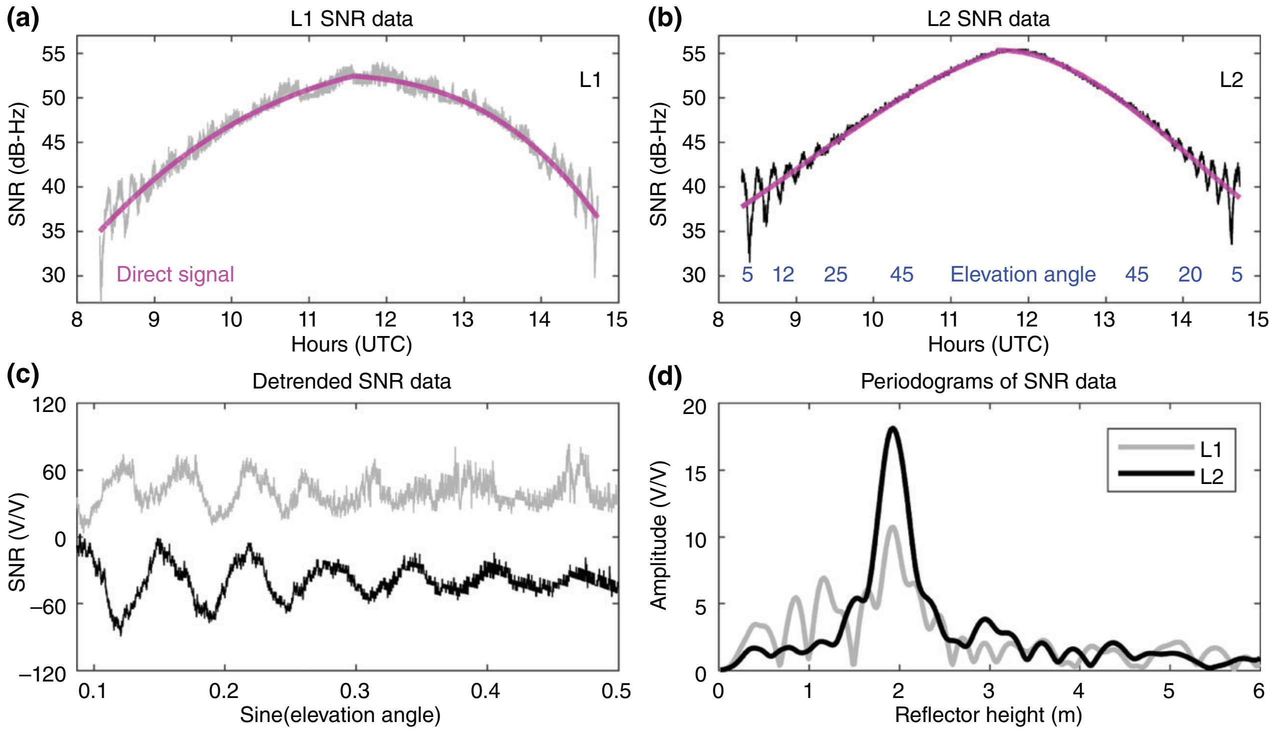

FIGURE 3 | (a, b) Signal-to-noise ratio (SNR) data are shown for the GPS L1 (gray) and L2 (black) frequency signals. The direct signal is represented by the low-order polynomial fit (magenta). Elevation angles corresponding to this time period are shown in blue. (c) Reflection data for L1 and L2 data after direct signal effect has been removed. The L1 and L2 data have been offset from zero for clarity. (d) Periodogram of the reflection data from panel (c) are shown. The *x*-axis is defined as the reflector height in meters, which is the vertical distance between the GPS antenna and the reflecting surface.

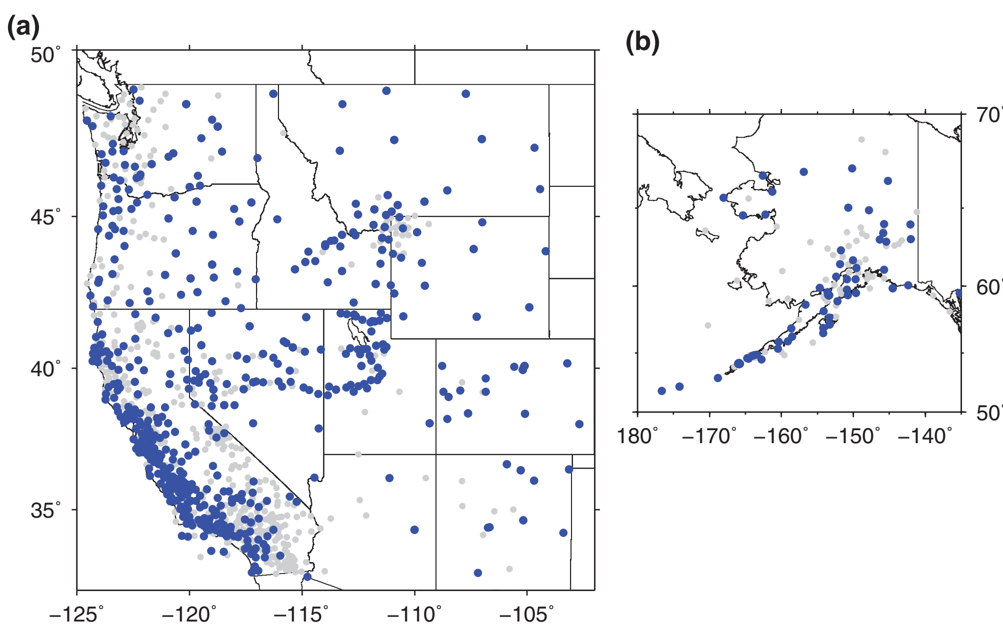

FIGURE 4 | All Plate Boundary Observatory (PBO) sites (a: western United States; b: Alaska) are shown in gray. Those with potential for GPS-IR have been highlighted in blue.

Snow Depth

The first GPS-IR measurements of snow depth were made at a flat mesa site south of Boulder, CO.[14] While the snow depth retrievals agreed within a few cm with manual measurements made over a 25 meter transect, it was also necessary to determine how well

GPS-IR works in more challenging environments. Niwot Ridge Long-term Ecological Research station was chosen because of its topographic variability (it is in a saddle at an elevation of ~3500 m), its extreme cold, and because it is impacted by very high winds. The site had the advantage of nearby internet access and an existing climatology study. The latter provided *in situ* measurements of snow depth at 2- to 4-week intervals at a network of poles spaced 100 m apart (Figure 5(a)). Although strictly speaking the pole in the photo might appear to be collocated with the GPS instrument, recall that the GPS-IR footprint is much, much larger (Figure 2(a)). Figure 5(b) shows GPS-IR snow depth measurements and *in situ* measurements from 2009 to 2015. They are in good agreement (<0.05 m) in terms of the temporal variations of snow depth and resolution of the manual measurements (0.1 m). One can also see that it is fortunate that the GPS antenna is 3 meters high, as snow depth in 2011 reached levels of ~2.5 m.

GPS-IR was also tested in a forested region at the Utah State Daniel Experimental Forest. The GPS antenna was placed at the northern end of a small meadow that was approximately 150 m × 150 m in size. The trees surrounding the meadow were taller than the GPS antenna, thus significantly reducing the number of reflected signals that could be reliably retrieved. Nevertheless, excellent agreement (0.04–0.06 m) has been reported between the GPS-IR derived snow depths and hand-measured snow depths (Figure 6).[20,28] Although PBO H_2O is now an operational network, it is also possible to extend snow depth time series to the time when the instrument was installed. Figure 7 shows such an example—a 14-year snow depth record for the GPS site in Barrow, AK.[20]

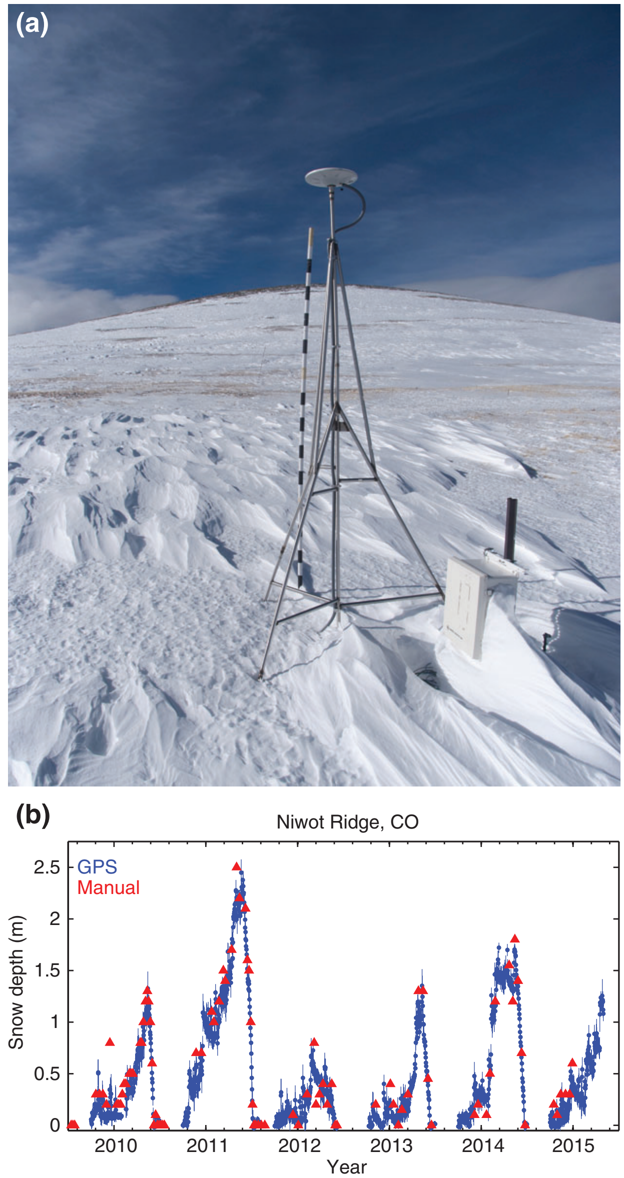

FIGURE 5 | (a) Photo of the Niwot Ridge GPS antenna. Snow depth is also measured at the black and white pole by the Niwot Ridge Long-Term Ecological Research group at 2-week intervals during the snow season. (b) Snow depth measured by GPS-IR (blue) and at the pole shown in panel (a) photograph (red).

Volumetric Soil Moisture

Without question, of the three parameters that are discussed here (snow depth, volumetric soil moisture, and vegetation water content), volumetric soil moisture is the most challenging to measure with GPS-IR. As noted previously, soil moisture variations are based on phase derived from SNR interferograms. To scale phase estimates to volumetric soil moisture, electromagnetic forward models are used.[24,25] The simplest model assumes a reflection from bare soil, while more sophisticated models assume soil covered by a variety of different vegetation canopies, such as grasses, shrublands, wheat, and alfalfa.[26] The retrieval algorithm used by PBO H_2O generally assumes low vegetation water content canopies, i.e., less than 1.5 kg/m^2. As PBO H_2O is primarily based in the semi-arid grasslands, savannas, and shrublands of the western United States, this fairly simple vegetation model works well. More complicated vegetation models for GPS-IR have also been successfully tested in croplands (alfalfa, wheat, and corn), but have only implemented for a few PBO H_2O sites.

A representative PBO H_2O volumetric soil moisture time series from a site in eastern New Mexico is shown in Figure 8. Note the strong correlation between soil moisture changes and precipitation events, followed by dry-downs. The soil moisture products have been validated by making *in situ*

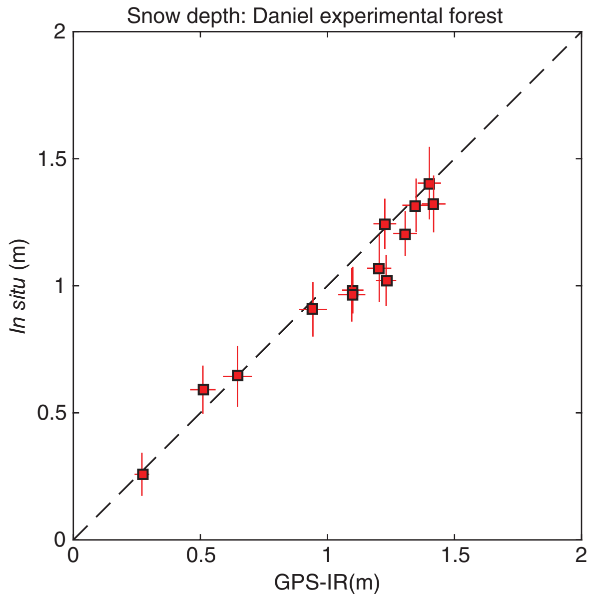

FIGURE 6 | Utah State Daniel Experimental Forest comparison between GPS-IR and *in situ* hand measurements measured in the GPS-IR footprint.

measurements at 10 sites over 2 years (Figure 9).[29] The root mean square error for these two datasets is 0.039 m^3/m^3, which meets the specifications for validation of satellite systems. Soil moisture data from PBO H_2O are currently used for validation of SMAP.[30]

Vegetation Water Content

The GPS-IR vegetation product is based on changes in reflection amplitude (Eq. (1)). Increases in vegetation water content decrease reflection amplitude and vice versa. PBO H_2O vegetation products are not currently defined in vegetation water content units (kg/m^2). Instead, the GPS-IR amplitudes have been

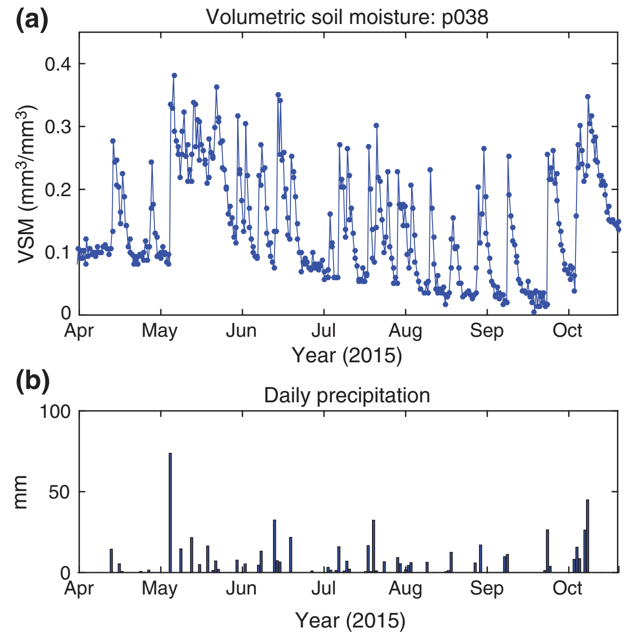

FIGURE 8 | (a) Volumetric soil moisture (VSM) estimated using GPS-IR for Plate Boundary Observatory site P038, located in eastern New Mexico. Soil moisture is estimated twice per day at this site. (b) Daily precipitation is measured with a Vaisala WXT520 sensor.

normalized by the maximum reflected amplitude; the sign has been reversed so that the GPS-IR vegetation product is aligned with vegetation growth.[27] There are a couple points to keep in mind when evaluating the PBO H_2O vegetation products. First, GPS-IR products are available daily; in contrast, Normalized Difference Vegetation Index (NDVI) is typically provided at 16-day increments. Secondly, GPS signals are not disturbed by cloud cover. This is quite different from optical measurements. A typical time GPS-IR vegetation time series for a PBO site in Northern California is shown in Figure 10. To provide

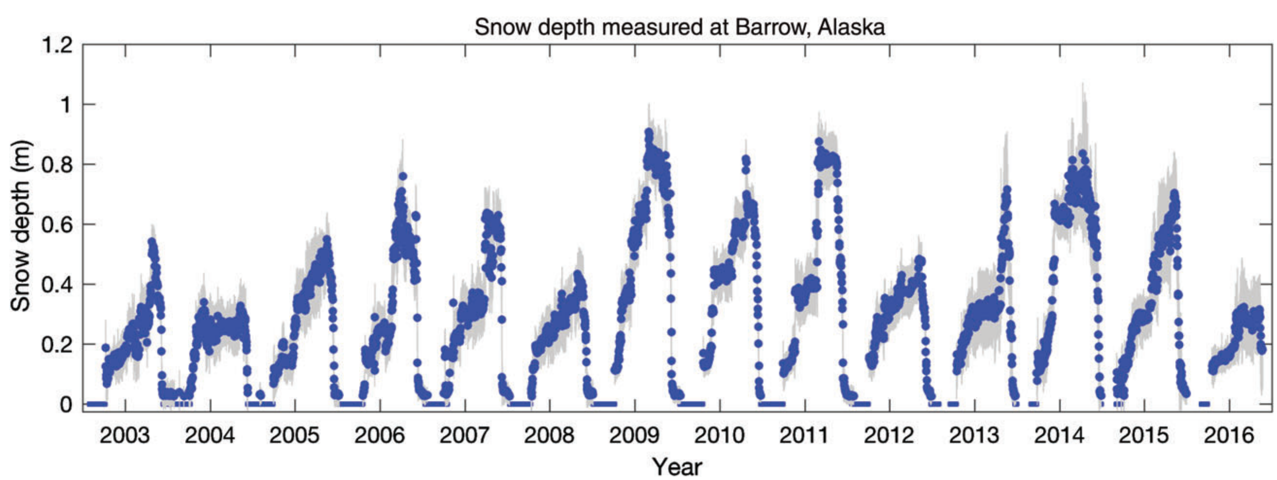

FIGURE 7 | GPS-IR measurements of snow depth at Barrow, AK (Plate Boundary Observatory site SG27). To improve clarity of the snow depth estimate in blue, one standard deviation error bars are shown in gray.

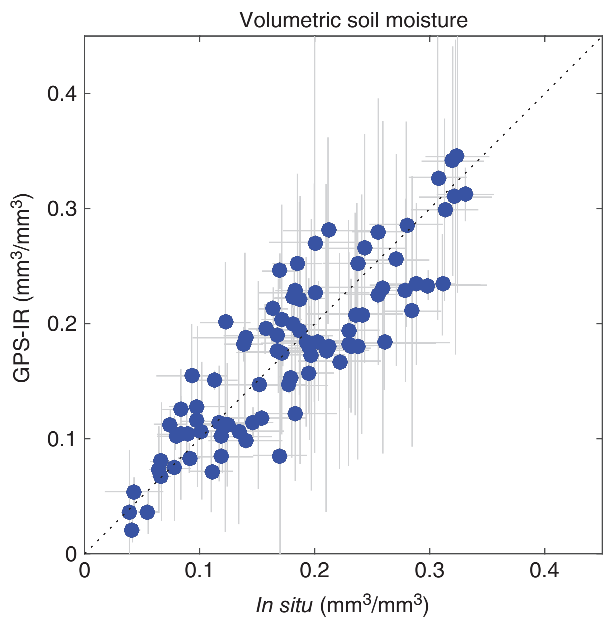

FIGURE 9 | Comparison between *in situ* soil moisture probes and GPS-IR. Error bars represent one standard deviation. Root mean square error is 0.039 mm^3/mm^3.

phenological context, NDVI data, an optical measurement, are also shown. The NDVI data measure greenness, and thus are correlated with chlorophyll production, vegetation density, leaf structure, etc. GPS-IR is correlated with vegetation water content; it only correlates well with NDVI in some climates.[31]

For the example site in Northern California, both the NDVI and GPS-IR show growing seasons in the first few months of the calendar year. However, the two measures differ in season length, with NDVI having a significantly longer season length.[31] It also shows a smaller sensitivity to the 2007 drought compared to GPS-IR. The R^2 for the NDVI and GPS-IR series is 0.27. The differences in the growing season are summarized in Figure 11(a), where NDVI's earlier green-up is highlighted by the dashed line. However, GPS-IR and NDVI senescence are synchronized (solid line). In contrast, a GPS-IR vegetation series for a site in eastern Wyoming shows a very high correlation with NDVI during both green-up and senescence. The R^2 between these the time series from Wyoming is much higher, 0.76 (Figure 11(b)). We attribute these dissimilar characteristics to differing

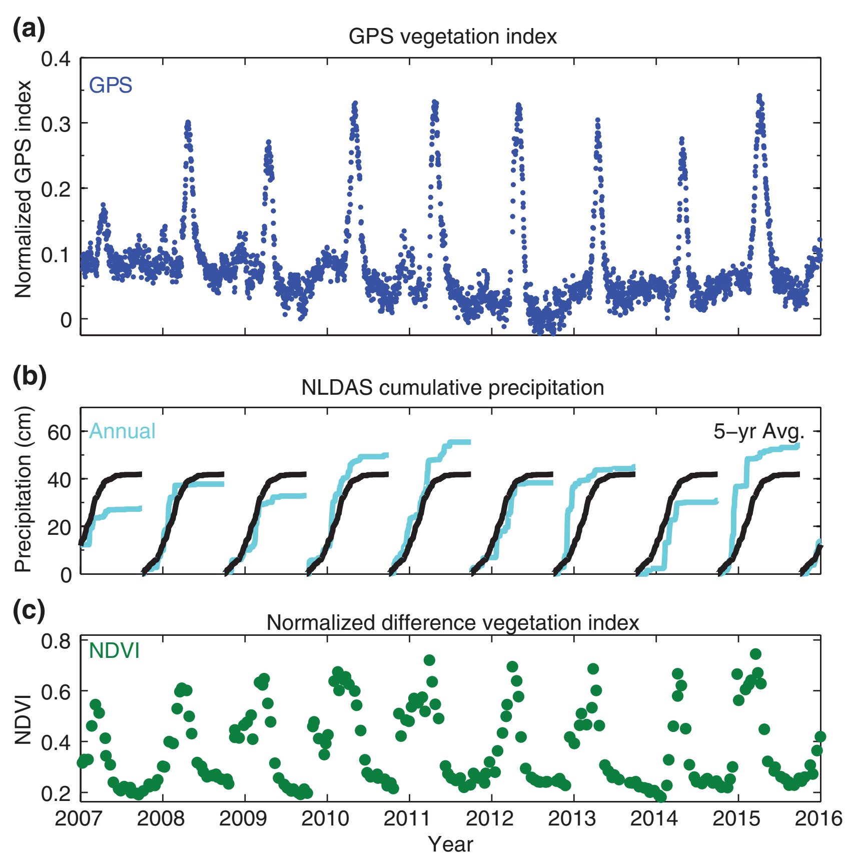

FIGURE 10 | (a) GPS vegetation index for Plate Boundary Observatory site P208. (b) Cumulative North American Land Data Assimilation System (NLDAS) precipitation. (c) Normalized Difference Vegetation Index.

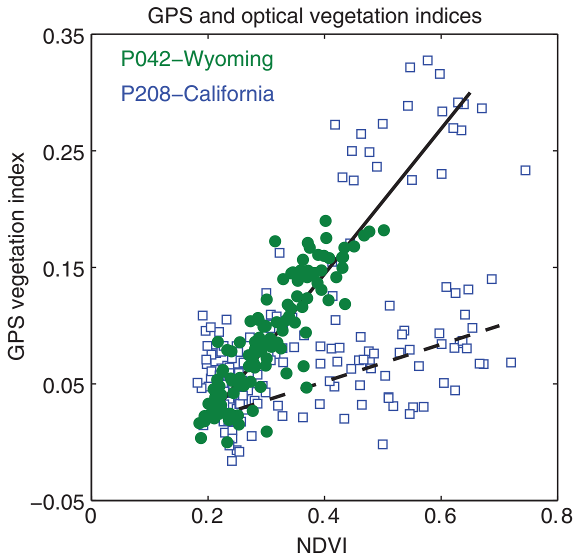

FIGURE 11 | Comparison between GPS-IR vegetation index and NDVI. The green-up period for the California site (blue symbols) is shown by the dashed line and the nondashed line is the senescent period. Results for a GPS site from eastern Wyoming (P042) are shown in green. At this site, there is a much stronger correlation between the GPS and NDVI data, and thus there is no depiction of separate green up and senescent periods.

climate conditions in California and Wyoming. In California plant growth and green-up occurs when temperatures are colder, whereas green-up and vegetation water content increase in the mountain west in the late spring and early summer when temperatures are warmer.[31]

One of the advantages of GPS-IR is access to GPS datasets with long records. Figure 12 shows such a compilation from PBO H_2O for a 9-year period. For each GPS site, the period from 2008 to 2012 was used to normalize the peak vegetation results so as to provide a point of comparison. Thus, a ratio of 130% is 30% greater than the 5-year average, and so on. These data make several things very clear. First, the very severe 2014 California drought could easily be seen in some areas beginning in 2012, worsening in 2013 before the most drastic variations were observed in 2014. Secondly, there is also a clear recovery over much of California in 2015. Because of the great density of PBO sites in California, one has the spatial resolution to evaluate variations in vegetation water content and NDVI along with temperature and precipitation drivers.

DISCUSSION

In the previous section, GPS-IR results for the PBO network were shown. Was there something about the PBO network that made it particularly well suited for GPS-IR? What are the prospects for applying GPS-IR to the global network of GPS sites?[5] In terms of the GPS equipment itself, the PBO network is pretty much like all other continuous GPS (CGPS) networks. In fact, many other GPS networks operate at higher sampling rates, track more signals, and use real-time telemetry, which makes them more advanced than PBO in those senses. However, it is relevant to acknowledge that the locations of PBO sites were guided by scientific questions. If the scientific questions to be answered required that sites be placed in rural areas (and thus operated with solar panels/batteries), the sites were located in rural areas. It is also true that many geoscientists and geodesists that operate CGPS networks avoid placing GPS antennas on or near buildings. They do so to avoid the positioning errors that would result in reflections from those buildings. They also avoid buildings because they are less stable than a well-built geodetic monument. CGPS operators with less stringent accuracy requirements more frequently locate their sites on buildings. This solves their power and telemetry problems and lessens concerns about theft and vandalism. Data from some of these CGPS sites may be useful for GPS-IR applications, but most of them are not.

This summary has focused entirely on GPS-IR. What about GNSS-IR, where reflected signals from the other Global Navigation Satellite System constellations (Glonass, Beidou, and Galileo) are used? There are two concerns. One is that many receivers in use today only track GPS signals. This is, for example, the case for the PBO. Some receivers only track GPS because the instruments are fairly old. As these older units are replaced, they will be upgraded to ones that can track all GNSS signals because this is what commercial vendors provide. Given the capital cost of upgrading CGPS units, conversion to GNSS-tracking will not take place immediately, but slowly over the next decade. A secondary issue is that other GNSS constellations do not have a daily repeating ground track. However, use of even a coarse digital elevation map should make it possible to use these GNSS signals for GNSS-IR. Initial results for GNSS-IR are very promising.[32]

PBO H_2O has taken advantage of existing infrastructure and data archives to retrieve long environmental records of snow depth, soil moisture, and vegetation water content. Similar results are likely from the global GNSS network.[5] What about new GNSS sites? Hopefully the results highlighted here will convince agencies that deploy and operate CGPS (and CGNSS) networks to chose these sites in an optimal way for both positioning and GNSS-IR. The costs

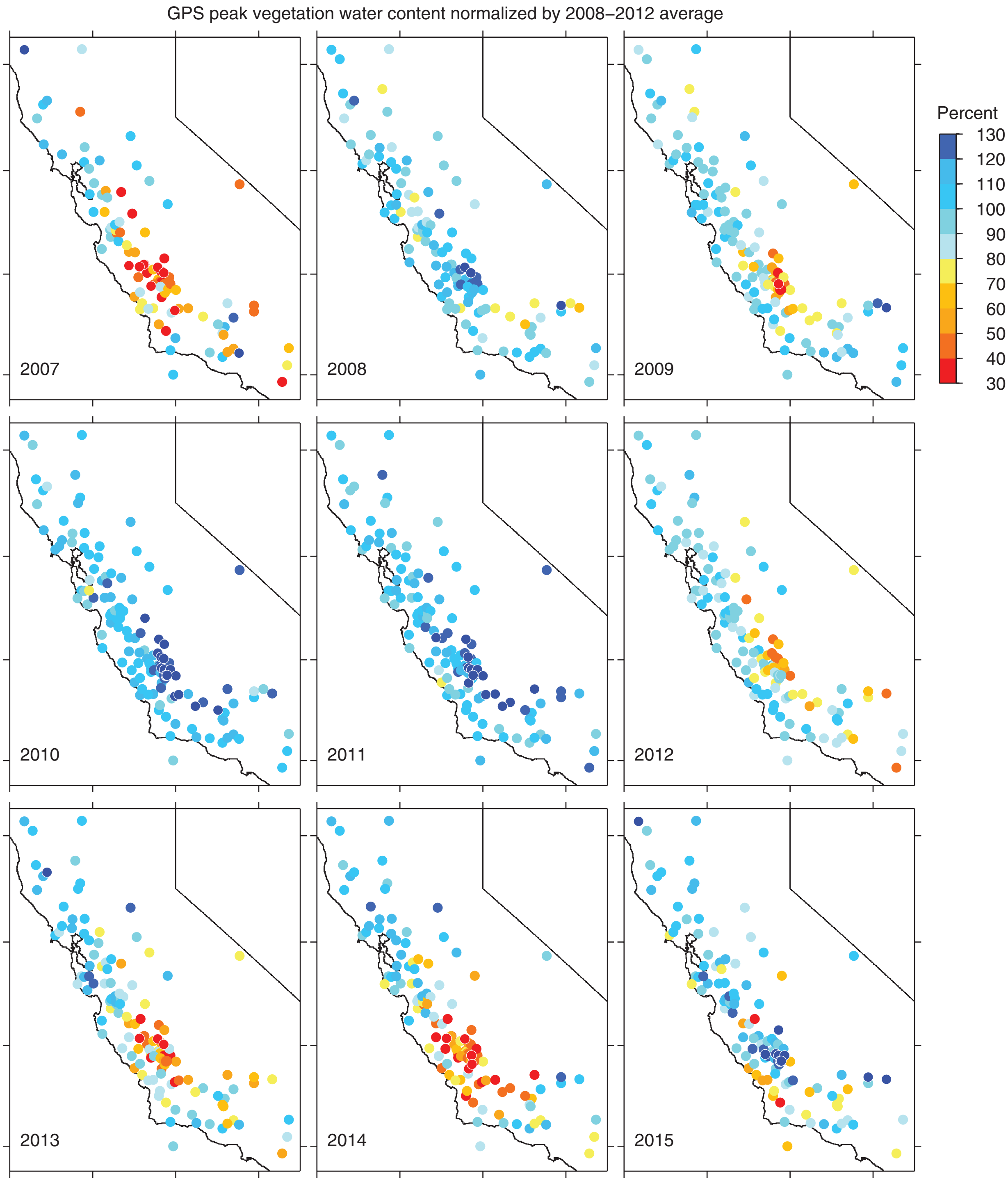

FIGURE 12 | Peak GPS-IR vegetation index for the years 2007–2015 for PBO sites in California. In each year, the peak is compared to the average for 2008–2012 and reported as a percentage as defined in the color bar.

of a CGPS site are not negligible (~$12,000 USD + telemetry). However, it is a robust system that typically requires little maintenance and has high data return. The primary requirement for GNSS-IR is that the GNSS antenna be located in close proximity to natural surfaces. However, if a roof top deployment is required for safety or access to power/telemetry, a GNSS site can still be valuable if it is placed at the edge of the roof rather than at the center. An important secondary constraint is that the natural surface be fairly planar. The rougher the surface, the less likely it is that GNSS-R will be able to successfully retrieve changes in soil moisture, vegetation water content, or snow depth. Keep in mind that not a single PBO site was installed in a way to make it more useful for GPS-IR applications, yet nearly 400 of them are currently being used for one of the three environmental products described here (Figure 4).

Is GPS-IR the best way to measure these environmental products? The simple answer is no. GPS-IR has trade-offs like any scientific instrument.

1. The GPS-IR soil moisture measurement is only valid for the near surface (top 5 cm); this restriction is set by the GPS frequency. On the plus side, this makes it ideal for validation of satellite sensors like SMAP that are using the same frequency band. Soil moisture cannot be measured by GPS-IR if the unit is placed near buildings and trees, but it has the advantage that it measures soil moisture over a much larger area than most other *in situ* probes.
2. The biggest limitation of GPS-IR for snow studies is that it does not directly provide snow water equivalent, which is a more desirable measurement than snow depth. However, GPS-IR measures snow depth over a much larger area than snow pillows or ultrasonic sensors, providing a more representative measurement. A GPS-IR snow water equivalent product can be estimated by modeling density.[28] GPS-IR cannot be used to measure snow depth in heavily forested regions, but PBO H_2O has shown that the method provides new measurements where there is little existing snow instrumentation.
3. GPS-IR provides excellent temporal sampling of vegetation water content variations, but it does not have the spatial sampling of a satellite system, such as provided by satellites measuring NDVI. However, GPS-IR is not impacted by clouds and is linked to vegetation water content, which is a complimentary measurement to NDVI.

All these issues aside, the most important attribute of GPS-IR is that it is economical. If one had infinite sums of money to design, deploy, and operate *in situ* sensors to measure soil moisture, snow depth, and vegetation water content, there would be no need to use GPS-IR. By supporting networks that are operated by another community (geodesy, geophysics, and surveyors), environmental scientists have an opportunity to take advantage of these long-term data streams, particularly as CGPS networks expand around the world. Environmental scientists could also deploy new CGPS sites in regions where large footprint measurements are desired. While not the focus of this review, GPS is also a practical way to measure tides and water levels in reservoirs, rivers, and lakes.[33] If properly situated, it is entirely feasible to measure soil moisture on one side of a GPS receiver and lake levels on the other, while simultaneously providing access to precise positioning for geodesists and surveyors,[3] and precipitable water vapor and total electronic content for atmospheric scientists.[8,9]

CONCLUSION

GPS reflectometry is an emerging field of environmental research. More than 20 years after the concept was first introduced,[34] we will soon see a dedicated space mission using reflectometry for the measurement of hurricane winds.[35] The European Space Agency is planning a reflectometry mission from the International Space Station.[36] Ground-based GPS reflection instruments have also been built and successfully employed.[37] In each of these cases, the instrument were designed to deliberately measure reflected signals. The development of GPS-IR has clearly benefited from these mission studies and ground-based reflectometry studies.[38] What sets GPS-IR apart is its use of commercial off the shelf instruments that can be operated by others who generally have no interest in hydrology. For these users, the multipath/reflected signals are a nuisance. GPS-IR is intrinsically a reverse engineering of these nuisance signals so that data from CGPS networks can be utilized by hydrologists. These data are valuable both to scientists and water managers, as well as being a cost-effective use of existing infrastructure.

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