Estimation of Snow Depth Using L1 GPS Signal-to-Noise Ratio Data

Kristine M. Larson and Eric E. Small

***Abstract*—Accurate measurements of snowpack properties are needed by scientists to better understand effects of climate variability on water resource availability. Satellite measurements currently assess snow cover rather than snow depth. Many *in situ* snow sensors/networks lack the necessary spatial and temporal sensitivity needed for such studies. Existing GPS networks are a potential source of new snow data for climate and hydrology studies, but current operational analyses only use signal-to-noise ratio (SNR) data from the new GPS signal centered at 1.2 GHz (L2C). These data are often unavailable in GPS archives. A snow depth algorithm that used the older (less precise) GPS signal centered at 1.5 GHz (L1) would provide longer snow depth time series that are needed by climate scientists. Here, an algorithm is developed to use the L1 SNR data. Snow depth estimates are derived for 23 sites for 5 years. These data are compared with existing snow depth time series derived from the L2C signal. They show an average bias of 1 cm and correlation of 0.95. Some of this disagreement is due to differences in the azimuthal coverage of the two datasets. The L1 snow depth solutions are also compared with *in situ* measurements, yielding a bias of −4 cm, comparable to the −6 cm bias found in a previous study of the L2C retrieval algorithm.**

***Index Terms*—Geoscience and remote sensing, radar, bistatic radar, Instrumentation and measurement, Reflectometry.**

I. Introduction

TWENTY years ago, a new application for GPS signals was presented by *Martin-Neira* [1]. Instead of the direct GPS signals used for positioning, Martin-Neira suggested using reflected GPS signals as the observable and outlined a method to use these signals to measure the ocean surface. Many of the subsequent GPS reflection experiments have been focused on altimetry and ocean wind applications [2]–[5]. In parallel, many groups have tested ground-based GPS instruments for reflection studies. In addition to water levels, ground targets for GPS reflectometry have included vegetation water content, soil moisture, and snow depth [6]–[10]. A third group of investigators has used geodetic instruments to measure reflected GPS signals. In contrast to the GPS reflectometry studies that use specially designed instruments to optimally retrieve the reflected signal, geodetic instruments only measure the interference of the direct and reflected signals. This geodetic-based method is called GPS Interferometric Reflectometry (GPS-IR). Geodetic instruments have the disadvantage that they were designed to suppress reflections, although they can be deployed to counteract that design feature [11]. The advantage of using geodetic instruments for reflectometry is that they are often operated by geoscientists and surveyors as permanent installations where the public has free access to these data.

In 2009, it was shown the GPS-IR technique could be used to successfully measure snow depth in the region surrounding a GPS site [12]. Validation of the technique with *in situ* measurements at 18 sites showed agreement ranged from 2 to 6 cm, with correlations of 0.97–0.99 for sites with longer time series [13]–[15]. These initial validations of GPS-IR for snow depth sensing were based on a modern GPS signal that is often not available in public data archives. In this contribution, we examine whether the original GPS (and noisier) signals are of sufficient quality to be used to measure snow depth. Since many station operators do not track the new GPS signals, an algorithm that uses the older signals would be particularly valuable for climate studies or satellite validation. The goal of this paper is to describe such an algorithm along with outlining some of its limitations.

II. Analysis of GPS SNR Signals for Snow Depth

GPS satellites were first launched in 1978. Since that time, they have all transmitted a civilian access (C/A) code on the L1 frequency (1.57542 GHz) and encrypted codes on both the L1 and L2 (1.22760 GHz) frequencies. These encrypted codes will be called L1P and L2P. In the past decade, the GPS program began to modernize the constellation. All GPS satellites launched since 2005 now include a civilian code on L2; it is called L2C. A third frequency (L5) was added to GPS starting in 2010; L5 signals are not discussed in this paper.

The Plate Boundary Observatory (PBO) H_2O project uses L2C signal-to-noise ratio (SNR) data collected by the EarthScope PBO to measure snow depth every day [16], [17]. Deployment of this 1100 station network began in 2004 and was completed in 2008. PBO initially installed a Trimble netRS geodetic-quality receiver at all sites. When instruments were replaced, typically the newer Trimble netR9 was used. Both units track the L1 and L2 frequencies and produce carrier phase, pseudorange, and SNR observables. The default tracking rate is 15 s. This particular model of receiver tracks the C/A code on L1 instead of both C/A and P codes. The primary observable used by geodesists on L2 is based on the L2P signal. The purpose of the network was to precisely

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Fig. 1. Photograph of GPS site at P038 in Portales, New Mexico (http://www.unavco.org). The antenna is under the hemispherical radome. The receiver is stored in a nearby equipment box. The antenna phase center at this site is approximately 2 meters above the soil surface.

measure tectonic deformation in the western United States (http://pbo.unavco.org). For this reason, the monument was built to be strongly coupled to bedrock whenever possible (Fig. 1). In all but a handful of locations, a PBO antenna is placed 1.5–2 m above the ground. As with many geodetic networks established in this time period, PBO receivers did not initially track the L2C signal. After establishing that the PBO receivers could track both the L2P and L2C signals without degrading the primary positioning products, the operators of the PBO network began routinely tracking L2C data in July 2011. For this reason, snow depth products for nearly all PBO H_2O sites begin in fall 2011.

The snow depth algorithm used by PBO H_2O is described in detail in [16], so only the basic principles are summarized here. SNR data reported on the L2C signal by the GPS receiver are used to extract the frequency of the interference of the direct and reflected signals. Because of the antenna gain pattern, reflected signal effects are primarily seen in data for elevation angles less than 30 degrees [Fig. 2(a)]. For natural planar surfaces, the frequency of the SNR data will be linearly related to the vertical distance between the GPS antenna phase center and the reflecting surface. Because the data are not sampled evenly and there are gaps, PBO H_2O uses the Lomb Scargle periodogram rather than a fast Fourier transform [Fig. 2(b)] to retrieve the dominant frequency, and thus "reflector height," of the SNR data. As shown in Fig. 2(b), after a snowfall, the reflector height decreases by the same amount.

Operationally PBO H_2O uses data from 30 days in the fall (but before snow has fallen) to define a "bare soil" reflector height value. This bare soil value is then subtracted from all subsequent reflector heights to define snow depth. Because no operational GPS site is located above a truly planar horizontal surface, each rising or setting satellite track is treated separately, including the determination of the bare soil value. The operational snow depth product for PBO H_2O is then the daily average of each satellite track snow depth estimate for a given day. After satellite tracks are selected, the primary quality control measures used are:

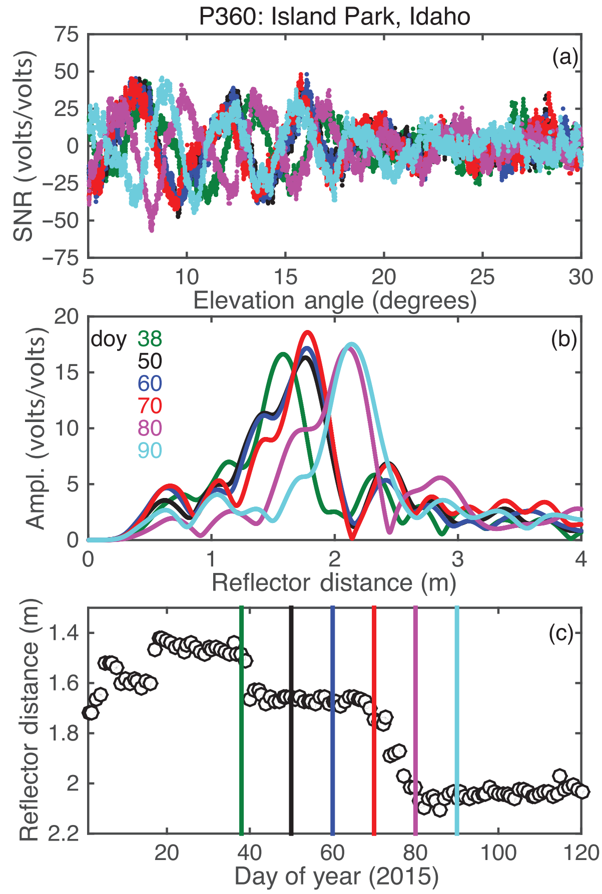

Fig. 2. (a) GPS SNR data for satellite 25 recorded at site P360 (Island Park, Idaho, http://www.unavco.org), colors defined as in (b). (b) Lomb Scargle periodograms for the data shown in the top panel. (c) Dominant reflector heights for days 1–120. Colored lines demark the days shown in the middle panel.

1) the standard deviation of the daily snow depth average;
2) the number of tracks that have a significant spectral peak amplitude.

The standard deviation test eliminates days where the Lomb Scargle has picked the wrong peak for one or more satellites. This occurs infrequently—in our experience, less than 0.5% of the days. The required peak spectral amplitude value has been set so that the peak of the periodogram must be four times larger than the background noise. At snow depth sites that are near agricultural fields, this metric helps eliminates days (primarily in May and June) when growing vegetation is attenuating the GPS reflections and producing nonzero snow depth values [18], [19]. For L2C snow solutions, the minimum number of tracks is set to 4 by default.

When PBO H_2O snow depth products were validated [13]–[15], there were only 9 L2C-transmitting satellites. This resulted in the potential spatial coverage shown in Fig. 3(a). Note that not all satellites produce the same number of satellite tracks for snow sensing. For example, satellite 1 rises and sets a total of four times each day, whereas satellite 17 only does so twice. Furthermore, not all satellite tracks can be used to estimate reflector height. Small arcs, such as those that rise to low maximum elevation angles (e.g., 10°) are always discarded by PBO H_2O. Certain azimuths cannot be used because of roads or buildings, or there is other human interference near

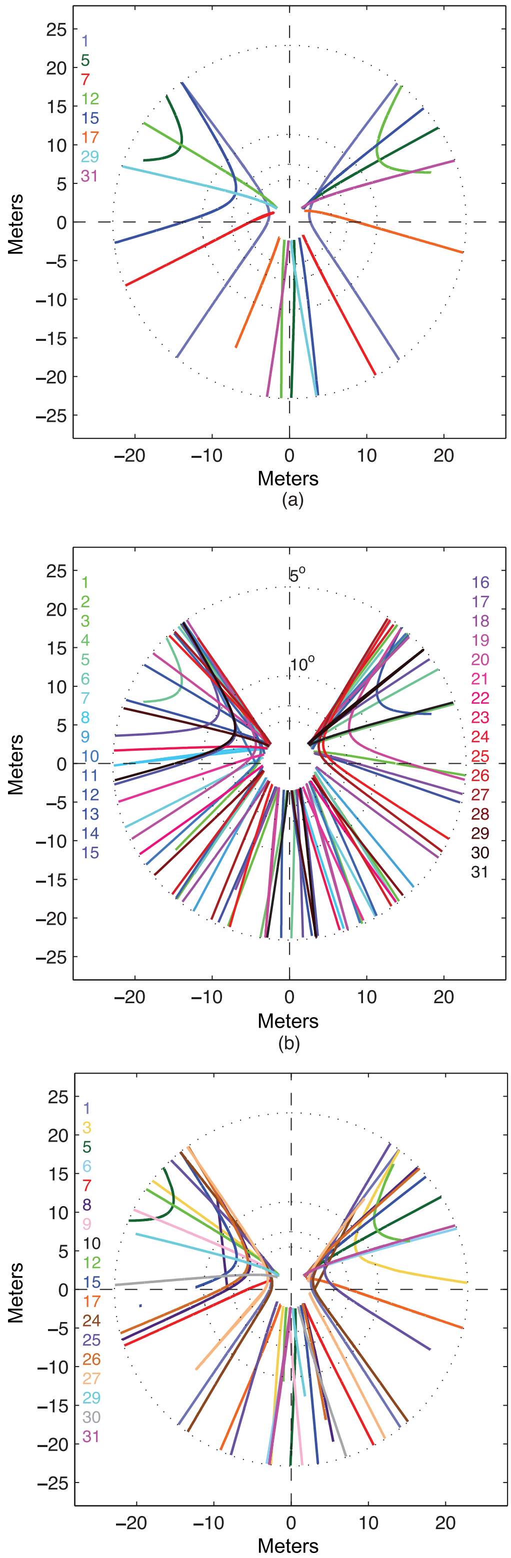

Fig. 3. (a) Reflection points for L2C satellites visible on day of year 90 in the year 2012. The circular dotted lines show reflection points for an antenna 2 m above the ground at elevation angles of 5°, 10°, 15°, and 20°. The colors are coded by satellite number. Reflection points are defined as the reflector height divided by the tangent of the satellite elevation angle. Only elevation angles below 25° are shown. Quadrants 1–4 are the northeast, northwest, southwest, and southeast map quadrants. (b) Same for L1 transmitting satellites. (c) L2C satellite tracks on day of year 280 in the year 2015.

the GPS site; there are also terrain obstructions. In other cases, the ground surface is too rough. The satellite coverage for the entire GPS constellation (as would be available if the L1 signal could be used) is shown in Fig. 3(b); it is clearly superior to coverage for the L2C constellation in 2012 and today's L2C constellation [Fig. 3(c)], which as of September 2015 consists of 17 satellites.

III. L1 Snow Depth Algorithm

The fundamentals of the snow depth algorithms for L1 and L2C GPS data are the same—peak frequencies are extracted from periodograms of SNR data from rising or setting satellite tracks. However, the SNR data recorded for L1 and L2C codes are not of the same quality. It is generally believed that the L1 SNR data are of lower quality because of cross-channel interference (see discussion in [16] and [20]). Unfortunately, this noise in the L1 SNR data is not random and manifests itself in systematic patterns. The impact of the L1 and L2C noise spectra can be viewed in terms of reflector height [Fig. (4)]. Here, reflector heights for 1 year are shown for a PBO H_2O site with very high data quality. During this year, there was very little snow, so the repeatability of the estimated reflector heights provides insight as to the precision of the L2C GPS-IR technique, 2–3 cm depending on the satellite track. Contrast these retrievals with the reflector height time series that was generated from the L1 signals. Given the large systematic variations in reflector height, it is not clear at all that a daily average of these reflector heights will result in an accurate snow depth estimate.

Satellite tracks used for the L2C PBO H_2O snow depth products are currently chosen manually. While this is only done once (after a new satellite is launched), it limits automation of the snow depth products. A better algorithm would automatically evaluate satellites tracks from the statistics of the data themselves. With that in mind, the L1 algorithm we have developed has the following steps.

1) Lomb Scargle reflector height periodograms are produced for all satellites tracks in all candidate azimuth ranges, typically at 30° increments, i.e., 30–60, 60–90, etc. The reflector height peak of the periodogram on each day for each rising and satellite satellite track is retained.
2) Bare soil reflector heights are first estimated for an azimuthal range using the median value of reflector heights in the fall, and large outliers are removed (those that are 30 cm from the median value).
3) Bare soil reflector heights are then estimated for each rising or setting satellite track. Standard deviation of the estimates used for the bare soil estimate must be less than 7 cm. Satellite tracks without at least 15 bare soil reflector height values are discarded.
4) A median filter is then used again to remove outliers before a daily mean is computed. A minimum number of satellite tracks are required to produce a daily snow depth average, which by default is set to 10.

For operational use, the only steps that allow intervention are step 1 (the azimuth ranges) and the number of tracks required. If, for several years, a given azimuth range never produces snow

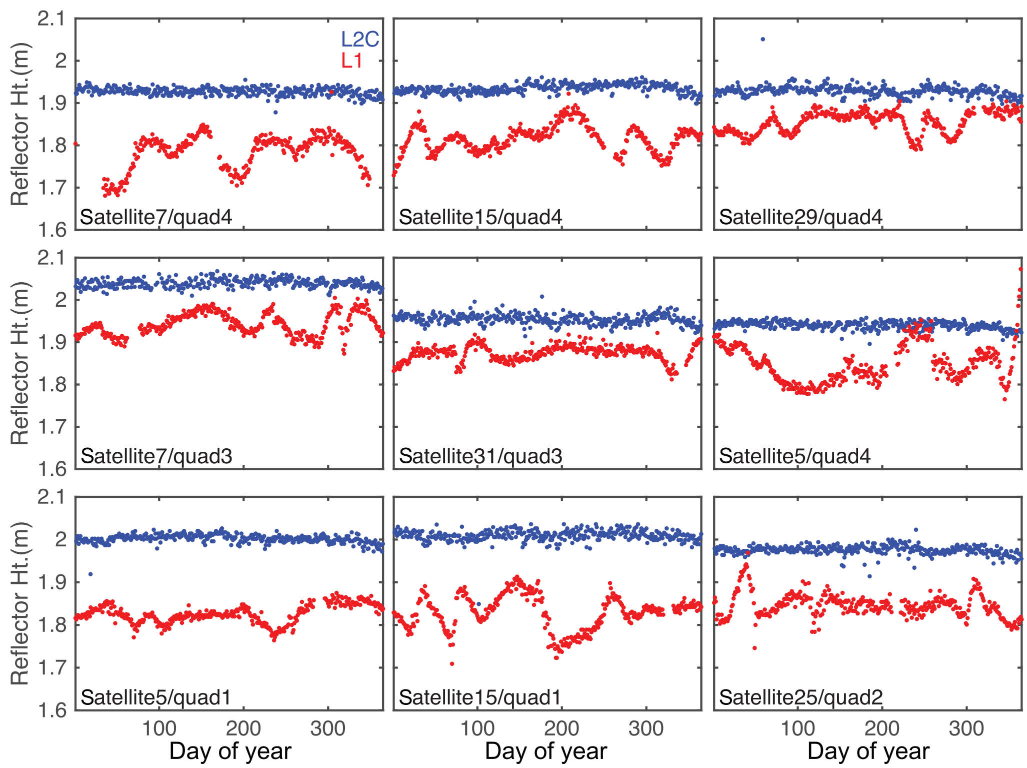

Fig. 4. Reflector height estimates for station P038 for a subset of rising/setting satellite tracks. Blue points are reflector height estimates using the L2C signal and red points are the same using L1 signals. The L1 and L2C traces have been offset for display purposes. Quadrant 1 is northeast with quadrant numbers increasing counterclockwise. Site information for P038 is available from http://pbo.unavco.org.

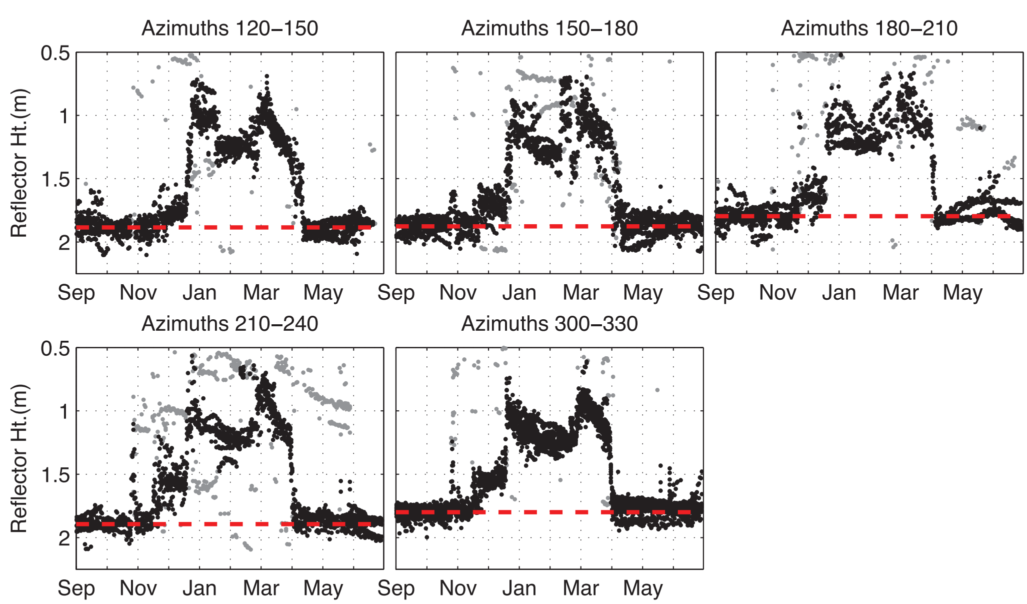

Fig. 5. Reflector height estimates are shown in black for station P030 for the 2011 water year. Each subplot shows the azimuth range defined in the title. Median bare soil reflector height estimates for each azimuth range are shown in red. Outliers detected by the algorithm are shown in gray.

depth retrievals, the operator can remove that azimuth range going forward. Doing so neither helps nor hurts the operational snow depth estimates but has the benefit of reducing CPU usage.

Fig. 5 shows reflector height for five azimuth ranges at PBO site P030. The presence of very large outliers at all times of year is noted. Many of these are removed at this stage via the median filter, where all tracks in a given azimuth range are binned together. Fig. 6 shows preliminary snow depth values for the same azimuth ranges with gross outliers removed and each satellite track set to its own bare soil value. The presence of apparent artifacts in these preliminary values is again noted, i.e., azimuth range 180–210 shows large snow depth values in May and June. Fig. 7 shows the final estimates for snow depth, which have again been screened with a median filter, so that those errant May and June values from step 2 have been

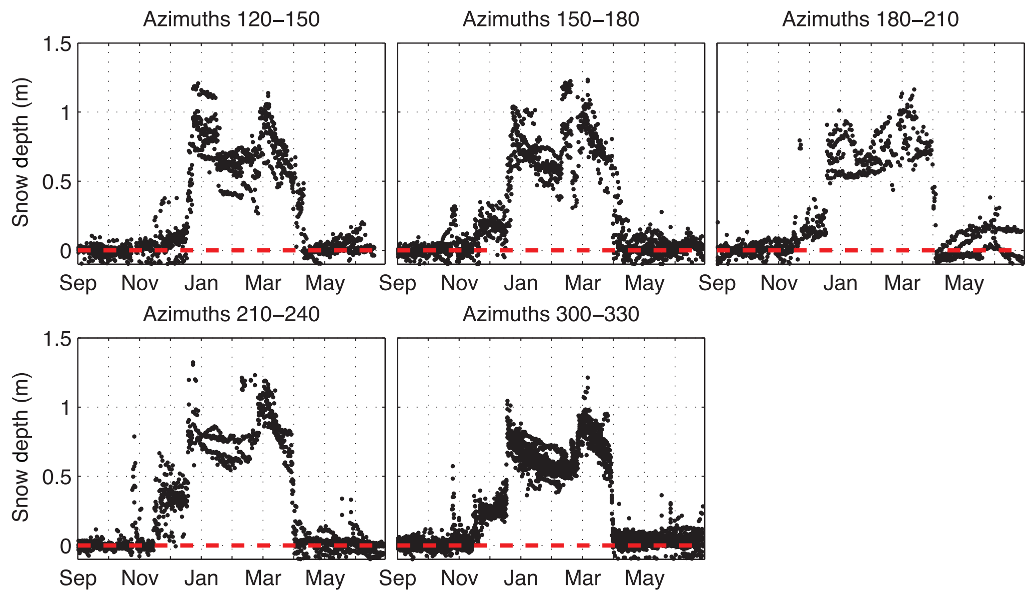

Fig. 6. Preliminary snow depth estimates for station P030 for the 2011 water year. Each satellite track has had a bare soil estimate removed, shown as the red dashed line, with the y-axis depicting snow depth.

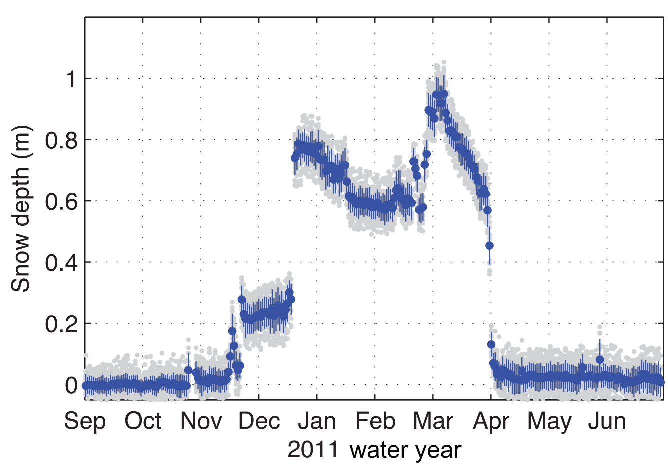

Fig. 7. L1-based snow depth estimates for station P030 for the 2011 water year (shown in blue). These are the average of the gray estimates, which represent individual satellite track estimates.

eliminated. Both the individual satellite track estimates of snow depth and the average value are shown. Note that the precision is best in September and October because these months were used to define the bare soil values. We found that the L1 algorithm performs the worst at sites with poorly resolved L2C solutions. In order to use the L2C data at these sites, we had lowered the required spectral peak amplitude. Given that the background noise level in L1 data is higher than for L2C data, we suspect that this helps explaining the poor performance of the L1 algorithm at these sites.

How well does the L1 analysis agree with the official L2C-based PBO H_2O snow depth products? Fig. 8 shows snow depth estimates for P030 compared over five years. The bias between L1 and L2C at this site is less than 1 cm; the correlation between the two snow depth time series is 0.99. The azimuths of satellite tracks used in each year are also shown in Fig. 8. One can see that there is general overlap between the L2C and L1 azimuth ranges, with the exception of the more westerly azimuths, where more L2C tracks have been used. There is also a general increase in the number of L2C tracks, particularly in the 2015 water year, which is due to the launch of three satellites in 2014 (the fourth satellite launched in December was not used in these comparisons).

IV. Discussion

For this study, we have computed snow depth estimates using L1 SNR data at 23 PBO H_2O sites (Table I). We have compared average snow depth results with L2C results for 3–5 years, depending on the site. In choosing sites, we deliberately excluded ephemeral snow sites, as those comparisons are dominated by a few snowstorms a year rather than persistent snow. The mean bias between L1- and L2C-based snow depth for these 23 sites is -1.2 cm. The correlations vary from 0.84 to 0.99, with an average correlation of 0.95. Some—but not all—of the variation in correlation and bias is due to differences in azimuthal coverage of the two datasets. We conclude from these statistics that the L1 solutions are sufficiently accurate to make publicly available to climate scientists and water managers. As noted in Table I, this doubles the timespan of the PBO H_2O snow depth dataset. In this study, we did not evaluate the L2P signals, but recent studies indicate that these can also be used to augment L2C snow depth retrievals [21]–[23].

The accuracy of the L2C snow depth method was previously addressed for 18 sites in the western U.S. [13]. In that study, *in situ* samples were taken on transects at 6 azimuths: 0°, 45°, 160°, 180°, 200°, and 315°. Each azimuth was sampled along a transect at 1-m intervals. For the comparison between *in situ* and L2C snow depth, averages were compared. The average *in situ* measurement was used as the accuracy metric deliberately so that it represented snow variability for the entire site. No azimuthal comparisons were made. Here, we use the same *in situ* data to assess accuracy of the L1 solutions.

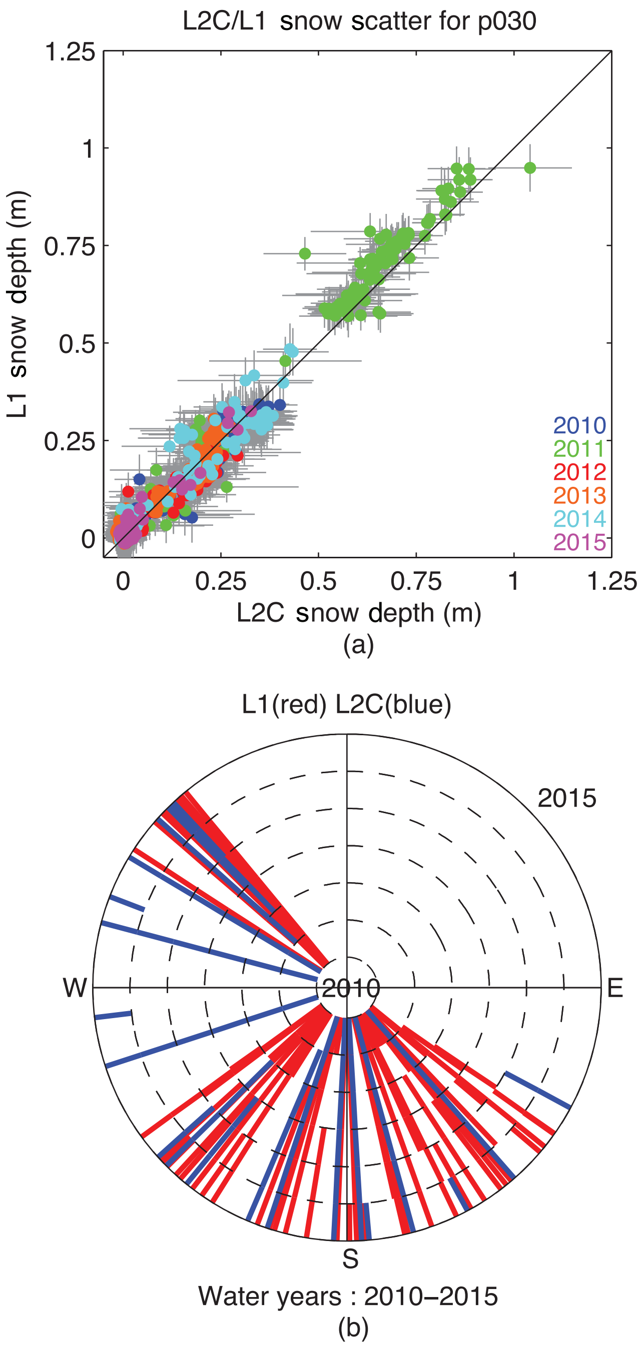

Fig. 8. (a) Comparison of L1 and L2C snow depth estimates for the water years 2010–2015. (b) Azimuthal coverage for snow depth estimates between 2010 and 2015.

TABLE I
SNOW DEPTH MEASUREMENTS FROM L1 DATASET. ALL L2C SERIES BEGIN IN 2012 EXCEPT FOR P101, P033, P360, P030, P676, AND P684.

	Lat.	Long.	Elev. (m)	Corr.	Bias (m)	Max. (m)	L1 start
<u>In situ sites</u>							
p019	43.30	−115.31	1683	0.98	-0.004	0.73	2008
p023	44.90	−116.10	1522	0.97	-0.035	0.81	2008
p101	41.69	−111.24	2016	0.99	0.007	0.86	2006
p118	40.63	−111.35	2083	0.98	0.001	0.48	2007
p350	43.53	−114.86	2388	0.99	-0.043	1.50	2009
p360	44.32	−111.45	1858	1.00	-0.009	0.96	2006
p676	44.65	−111.34	2190	0.98	-0.033	0.76	2007
p683	42.83	−111.73	2066	0.92	-0.026	0.58	2007
blw2	42.77	−109.56	2216	0.90	-0.023	0.57	2007
p025	48.73	−116.29	696	0.92	-0.014	0.45	2008
p030	41.75	−110.51	2150	0.99	-0.005	0.43	2006
p031	39.52	−107.91	1658	0.89	-0.004	0.42	2007
p033	43.95	−107.39	1376	0.92	-0.003	0.42	2007
p044	40.17	−103.22	1411	0.92	-0.005	0.38	2006
p046	47.03	−113.33	1291	0.89	-0.039	0.91	2007
p052	47.37	−107.02	859	0.96	-0.006	0.40	2007
p346	39.79	−120.87	2039	0.99	0.004	1.41	2009
p351	43.87	−114.72	2693	0.99	-0.010	1.47	2009
p413	48.43	−120.15	501	0.98	-0.018	0.60	2009
p641	37.88	−118.85	2527	0.92	0.005	0.40	2009
p684	43.92	−111.45	1694	0.97	-0.006	0.38	2006
p685	44.07	−111.83	1608	0.87	-0.008	0.46	2009

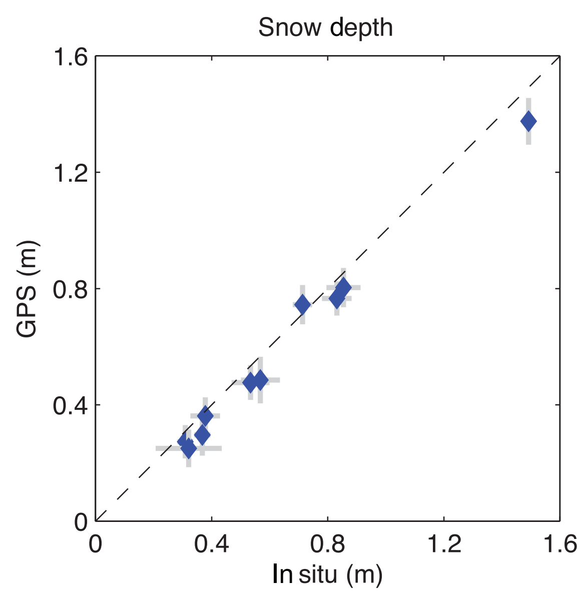

Fig. 9. Comparison of L1-based snow depth estimates for selected azimuths and *in situ* measurements.

We excluded some of the sites used in [13] because of the followings.

1) They represent measuring snow depth values of zero (P030 and P353).
2) The L1 algorithm failed (P455, P029).
3) The snow levels were too close to the antenna when the *in situ* measurements were made (P351).
4) There are no older L1 datasets to test (RN86).

Instead of comparing to an average of all *in situ* data as was done in [13], in Fig. 9, we compare the L1 snow depth retrievals in the same azimuth ranges as the *in situ* data. It is clear that the GPS snow depths are negatively biased compared to the *in situ* measurements; this bias is -4.1 cm. This is close to the previously reported value of -6 cm.

V. CONCLUSION

PBO H_2O will continue to base their operational snow depth products on the L2C SNR data. However, this paper demonstrates that if L1 SNR data are available, a suitable snow depth product can also be derived at many sites that agrees well with both L2C retrievals and *in situ* measurements. This algorithm is especially valuable as many geodetic networks do not track the L2C signal or if they do, they do not archive these data. Quality control must be much stricter to be able to use the L1 SNR data for snow depth estimation, with particular difficulties using these observations when vegetation begins to grow in May and June (in the western U.S.). However, as long as care is taken, the L1 data can be used to provide a precise and accurate snow depth time series for a decade or more at many sites in the western United States.

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