Daily Snow Depth and SWE from GPS Signal-to-Noise Ratios, Version 1

USER GUIDE

How to Cite These Data

As a condition of using these data, you must include a citation:

Larson, K. M. and E. E. Small. 2017. *Daily Snow Depth and SWE from GPS Signal-to-Noise Ratios, Version 1*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/Z02Y1HGNFXCH. [Date Accessed].

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FOR CURRENT INFORMATION, VISIT https://nsidc.org/data/NSIDC-0722

National Snow and Ice Data Center

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1 DETAILED DATA DESCRIPTION

Data are provided for 223 stations located primarily in the United States and predominantly western states. Data are also available for seven sites in Canada, three in Greenland, and one in Sweden (see Table 2 and Table 3 for more information).

> The SNOpack TELemetry (SNOTEL) network comprises more than 800 automated data collection sites located in remote, high-elevation mountain watersheds in the western U.S. SNOTEL sites monitor climatic conditions including snowpack, precipitation, and air temperature, and transmit the data to a central repository called the Water and Climate Information System.

1.1 Format

Comma Separated Values (.csv)

1.2 File and Directory Structure

Data files are available on the HTTPS site in the `https://daacdata.apps.nsidc.org/pub/DATASETS/nsidc0722_sd_swe_gps_v01/` directory. This directory contains a .csv file for each site.

1.3 File Naming Convention

Example File Name: `ab13_snow_v1.csv`

[SITE]_snow_v1.csv, where SITE is a four-character site identifier.

For a list of site IDs, consult the station-list.csv file. This file also specifies each site's latitude, longitude, and location (US state, Canadian province or territory, or Greenland), data start date, and whether or not (1 or 0) a nearby SNOTEL site was used to calculate SWE.

1.4 File Contents

The first 14 rows of the .csv file contain details about the data set plus station-specific metadata including latitude, longitude, and elevation (meters). Row 15 contains the column headers described in the following table:

Table 1. Data File Column Headings

Column	Name	Notes
1	year	—
2	month	—
3	day	—
4	doy	Day of year
5	snowDepth(m)	Snow depth in meters
6	StdErr(m)	Snow depth standard error in meters
7	swe(m)	Snow–water equivalent in meters
8	sweStdError(m)	Snow–water equivalent standard error in meters
9	FractionalYear	Fractional year. Value is expressed as [yyyy].[frac], where frac=doy/365 (or 366). For example, 2011.67 = day of the year 245 in 2011.

1.5 File Size

Data files are between 14 KB–290 KB. The complete set of files is approximately 22 MB.

1.6 Spatial Coverage

Sites are located primarily in the western United States, including Alaska; additional US sites are located in Hawaii (Mauna Kea), Indiana, Iowa, Kansas, Minnesota, Ohio, and Wisconsin. Data are also available at seven locations in Canada, one in Greenland, and one in Sweden.

Refer to Figure 1 to see how the stations are distributed throughout the US, including Alaska. Tables 2 and 3 breakdown the number of sites by US state and non-US locations, respectively. For a complete list of sites consult the station-list.csv file. This file specifies each site's latitude, longitude, and location (US state, Canadian province or territory, or Greenland), data start date, and whether or not (1 or 0) a nearby SNOTEL site was used to calculate SWE. To view, browse, and search for sites on an interactive map, visit the PBOH2O Data Portal | Snow Web site.

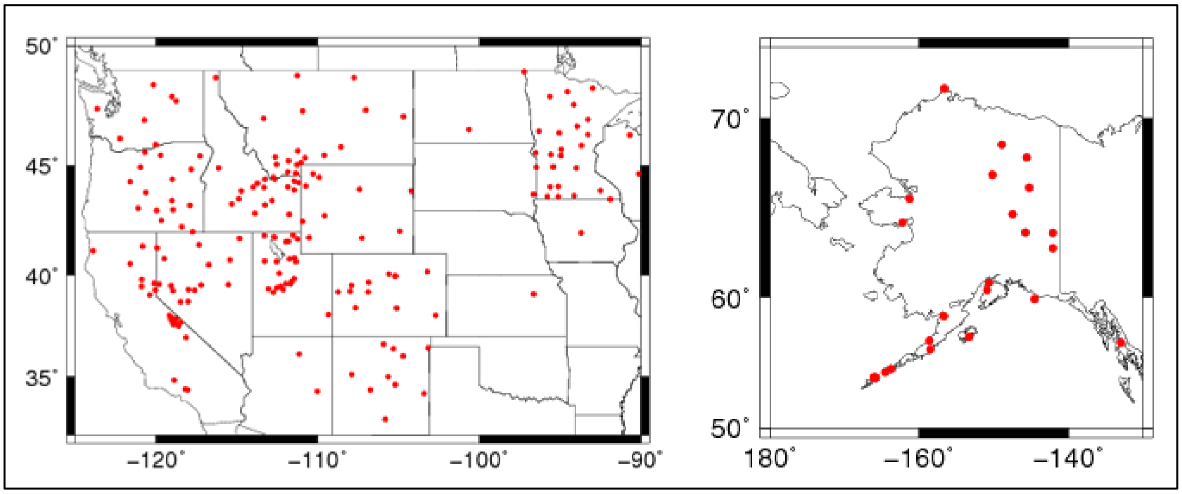

Figure 1. Maps showing approximate location of snow depth estimates in the continental US (left) and Alaska (right)

Table 2. Number of US Sites per State

US State	# of Sites	US State	# Sites
AK	25	ND	1
AZ	2	NM	10
CA	22	NV	15
CO	12	OH	1
HI	1	OR	16
IA	1	SD	1
ID	20	UT	23
IN	1	WA	7
KS	1	WI	2
MN	25	WY	10
MT	16		

Table 3. Number of Non-US Sites per Region

Region	# of Sites
AB, CA	1
NU, CA	4
NB, CA	1
NT, CA	1
Greenland	3
Sweden	1

1.6.1 Spatial Resolution

Snow depth corresponds to a roughly 1000 m^2 footprint surrounding the antenna. However, this value depends on a number of site-specific variables such as vegetation and local topography.

1.7 Temporal Coverage

Temporal coverage varies by site. The station-list.csv file lists each site's data start date, latitude, longitude, and location (US state, Canadian province or territory, or Greenland), plus whether or not (1 or 0) a nearby SNOTEL site was used to calculate SWE.

1.7.1 Temporal Resolution

Daily

1.8 Parameter or Variable

1.8.1 Parameter Description

This data set reports the following parameters:

- Snow depth (m)
- Snow depth standard error (m)
- Snow–water equivalent (m)
- Snow–water equivalent standard error (m)

2 SOFTWARE AND TOOLS

2.1 Software and Tools

Comma-separated value (.csv) files can be accessed using spreadsheet software or applications that can read ASCII text.

3 DATA ACQUISITION AND PROCESSING

3.1 Theory of Measurements

Previous studies have demonstrated that changes in snow depth can be derived from modulations in the GPS SNRs recorded by a geodetic-quality GPS receiver with its antenna in a standard geodetic orientation. Because hundreds of GPS receivers are installed in snowy regions in the

U.S., for plate deformation studies, surveying, and weather monitoring, these receivers can provide cryospheric scientists with a network of snow depth monitoring stations.

Snow water equivalent (SWE) is an important parameter for hydrological study because it represents the amount of water potentially available for runoff. As SWE is the product of snow density and snow depth, SWE can be calculated from GPS snow depth measurements given suitable estimates of snow density.

3.2 Data Acquisition Methods

The majority of stations in this data set are part of the Plate Boundary Observatory (PBO), a network of permanent, continuously operating Global Positioning System stations operated by UNAVCO, Inc. Twenty-five sites are operated by the Minnesota Department of Transportation.

3.3 Derivation Techniques and Algorithms

Sensing changes in the height of the snow surface from GPS SNR modulations is a complex procedure that varies somewhat depending on specific site characteristics and in particular the availability of the recently adopted L2C signal, which broadcasts at a higher effective power than the legacy L1 C/A. The following sections, adapted from Larson, K.M. and F.G. Nievinski, 2013, provide a general outline of the approach used for stations with L2C SNR data, the majority of sites in this data set. In cases where the L2C signal was not available, L1 SNR data were used following the procedure described in Larson, K.M. and E.E. Small, 2016. The fundamentals of the snow depth algorithms for L1 and L2C GPS SNR data are the same.

The three sites in the Greenland interior report snow accumulation, not snow depth, using the approach described in Larson, K.M., J. Wahr, and P. Kuipers Munneke, 2015. This method was developed to measure changes in snow depth at GPS stations with antennas mounted on poles sunk in the firn surface. Antennas mounted in this manner experience vertical displacements due to firn densification and downward motions of the ice below the firn. No SWE is reported for these stations.

3.3.1 Snow Depth

Snow depth is calculated using SNR observations from rising or setting GPS satellite tracks (elevation angle between 5° and 30°). These GPS data are generally made available to the public in an ASCII format called RINEX (Receiver Independent Exchange format). Although the L1 and L2 carrier phases (and pseudorange) are the primary observables used by geodesists and surveyors, many network operators also archive the so-called S1 and S2 observables, referred to as signal strength in the RINEX specifications. Standardized RINEX S1/S2 corresponds to the quantity called carrier-to-noise-density ratio (C/N_0): the ratio of signal power to the noise power spectral density. SNR is related to C/N_0through the noise bandwidth (B) as SNR = $(C/N_0)/B$ (Joseph, 2010), thus having units of decibels in logarithmic scale, watts per watt in linear scale, or volts per volt when taking the square root.

Figure 1a shows the general features of L2C SNR data from a code-correlating receiver. In the absence of multipath, SNR values smoothly rise from ~35 dB to a peak of ~52 dB, a consequence primarily of the direct or line-of-sight power (Pd) and secondarily the reflected power (P_r):

$$SNR \propto P_d + P_r + (P_d P_r)^{1/2} \cos\Phi$$ **(Equation 1)**

This trend is determined by the satellite transmitted power, the antenna gain pattern, and whether the receiver is using code-enabled tracking methods. In addition, modulations are superimposed on the trend at the rising end of the arc; these peaks and troughs are constructive and destructive interference caused by coherent multipath, dictated by the reflection phase (Φ). The frequency, phase, and amplitude of the multipath modulations are caused by a variety of factors, including the composition, geometry, and roughness of the reflecting surface. However, since the trend is not of interest, a low-order polynomial can be fit to the data to remove it.

The detrended SNR modulations seen in Figure 1b are typical for an antenna ~2 m above the ground and a relatively strong ground reflector. The amplitude of the modulation decreases as the satellite rises and its elevation angle increases; this is primarily due to the antenna gain pattern, which does a better job of suppressing multipath at higher elevation angles. At lower elevation angles, reflections off dielectric surfaces do not suffer as much polarization reversal, therefore even geodetic-quality antennas subject near-grazing snow reflections to as much gain as the direct signal.

The fundamental requirement of GPS snow sensing is that the area surrounding the GPS antenna acts as a specular reflector (Larson et al., 2009; Ozeki and Heki, 2012). For this to occur, it suffices that the surface be nearly planar, large enough to accommodate lower elevation angles, and free of substantial vegetation. A detailed explanation of the model for GPS multipath based on geodetic antennas and planar-layered media can be found in Zavorotny et al., 2010. Example model predictions for snow effects are also given in Larson et al., 2009. The key point for snow sensing is that the dominant GPS reflection occurs at the air-snow interface. For horizontal planar reflectors and the choke-ring GPS antenna used by PBO stations, the multipath modulation frequency is constant for the sine of the satellite elevation angle (θ), meaning that detrended SNR signals can be modeled very simply as a sinusoid:

$$SNR - P_d - P_r = A\cos(4\pi h \lambda^{-1} \sin\theta + \varphi)$$ **(Equation 2)**

The amplitude A represents an average of the variable factor $(P_d P_r)^{1/2}$ over the arc span. The parameter h is the vertical distance between the antenna phase center and the snow surface; λ is the GPS carrier wavelength (for the L2 frequency, ~24.4 cm).

Snow depth is defined as:

snow depth = (vertical distance to the ground) − (vertical distance to the snow layer) **(Equation 3)**

The first term, the vertical distance to the ground, cannot be assumed to equal the height of the antenna above the ground immediately under it—the distance will be greater downhill and smaller uphill and even small ground tilting angles translate into several tens of centimeters at the large horizontal distances involved. However, in practice SNR data can be used to estimate the vertical distance to the ground in the same manner as the distance to the snow surface. This means that bare ground must be observed before or after it becomes snow-covered, in summertime then winter. Such a topographic bias remains stable over time as long as satellites have repeatable ground tracks, which is the case for GPS.

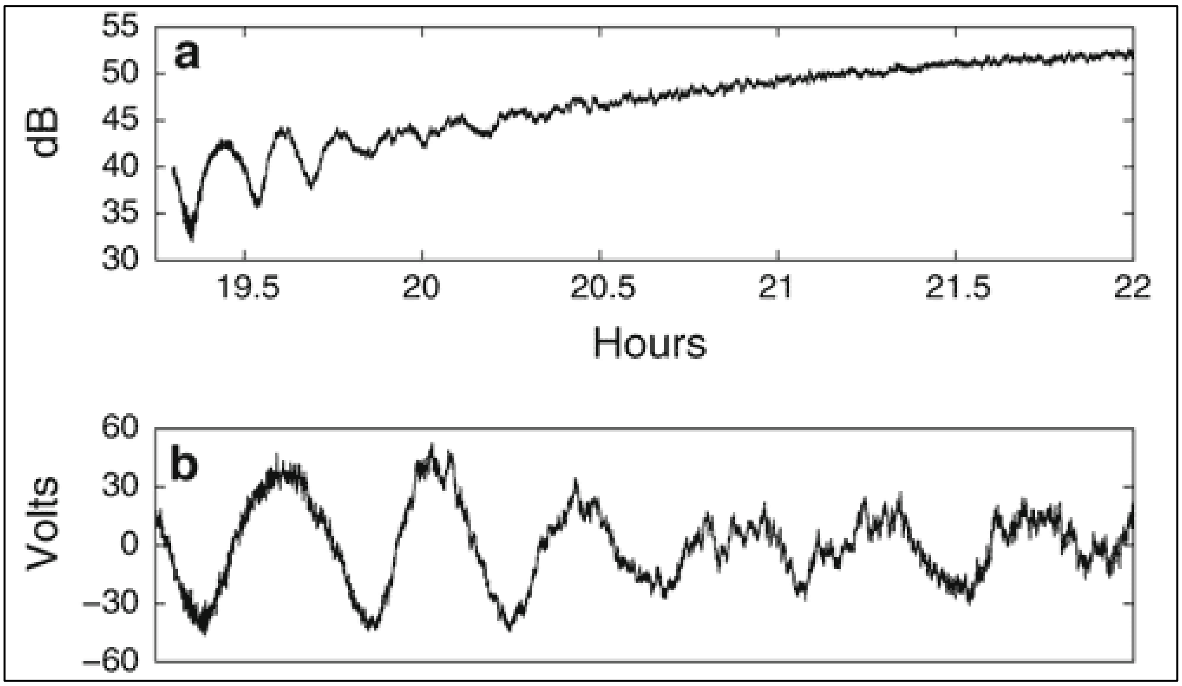

Figure 2. a) Recorded L2C SNR data for a PBO receiver; b) rising arc of SNR data, detrended with a second-order polynomial and converted from dB to linear units (for simplicity, volts). Figure adapted from Larson, K.M. and F.G. Nievinski, 2013

Given suitable site characteristics and a strong reflector, snow depths can be inferred by generating periodograms of the SNR traces and examining modulations in the peak frequencies. In Figure 2, panel a) shows three representative detrended SNR traces from a PBO site (p101), on dates specifically chosen to represent snow-free conditions, ~50 cm, and ~100 cm of snow on the ground. Panel e) shows the Lomb-Scargle periodogram (LSP) computed for each SNR trace. On each day, the retrieved frequencies have been converted to a reflector height (Equation 2). The changes in reflector height are pronounced for this satellite track, and the peaks are much greater than the background LSP noise, indicating a strong specular reflection. Panels b) and f) show similar results for site p360. Again, this site exhibits strong peaks, although on day of year 300, the LSP estimate is weakened by missing SNR data.

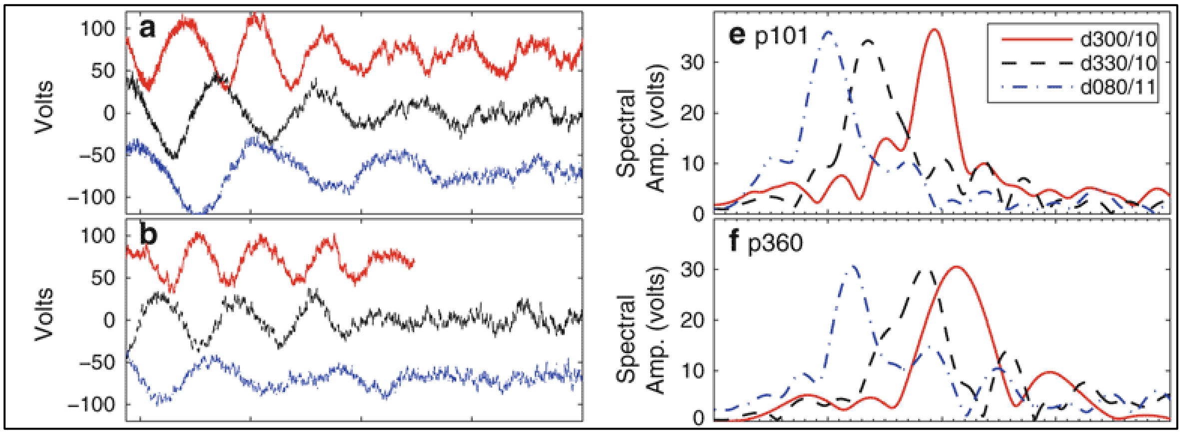

Figure 3. Panels a) and b) show representative, detrended SNR data from two PBO stations, p101 and p360, on days with bare soil (d300), ~50 cm of snow (d330), and ~100 cm of snow (d80). Lomb-Scargle periodograms computed from the SNR data are shown in panels e) and f). Figure adapted from Larson, K.M. and F.G. Nievinski, 2013

3.3.2 Snow Water Equivalent (SWE)

SWE is calculated as the product of GPS-derived snow depth and snow density. Snow densities were generated following one of two approaches. For GPS sites located within 70 km of a SNOTEL monitoring station, snow density is modeled following McCreight, J. L. and E. E. Small, 2014. Densities at sites with no nearby SNOTEL data were estimated using Sturm et al., 2010.

3.3.3 Quality Assessment

Snow depth accuracy is estimated to be approximately 5 cm; SWE is approximately 2 cm. See Gutmann, E. et al., 2011; McCreight, J. L., E.E. Small, and K.M. Larson, 2014; and Larson, K.M. and E.E. Small, 2016 for details.

4 REFERENCES AND RELATED PUBLICATIONS

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4.1 Related Data Collections

Snow Data Assimilation System (SNODAS) Data Sets at NSIDC

Canadian Meteorological Centre (CMC) Daily Snow Depth Analysis Data

4.2 Related Websites

PBO H_2O Data Portal | Snow

Snow Telemetry (SNOTEL) and Snow Course Data and Products

5 CONTACTS AND ACKNOWLEDGMENTS

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6 DOCUMENT INFORMATION

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6.2 Date Last Updated

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