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Can we measure snow depth with GPS receivers?

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[1] Snow is an important component of the climate system and a critical storage component in the hydrologic cycle. However, *in situ* observations of snow distribution are sparse, and remotely sensed products are imprecise and only available at a coarse spatial scale. GPS geodesists have long recognized that snow can affect a GPS signal, but it has not been shown that a GPS receiver placed in a standard geodetic orientation can be used to measure snow depth. In this paper, it is shown that changes in snow depth can be clearly tracked in the corresponding multipath modulation of the GPS signal. Results for two spring 2009 snowstorms in Colorado show strong agreement between GPS snow depth estimates, field measurements, and nearby ultrasonic snow depth sensors. Because there are hundreds of geodetic GPS receivers operating in snowy regions of the U.S., it is possible that GPS receivers installed for plate deformation studies, surveying, and weather monitoring could be used to also estimate snow depth. **Citation:** Larson, K. M., E. D. Gutmann, V. U. Zavorotny, J. J. Braun, M. W. Williams, and F. G. Nievinski (2009), Can we measure snow depth with GPS receivers?, *Geophys. Res. Lett.*, *36*, L17502, doi:10.1029/2009GL039430.

1. Introduction

[2] Snow is an important component of both regional and global climate systems, as well as a critical storage component in the hydrologic cycle. Snow water equivalence (SWE), the product of snow density and depth, is the most important parameter for hydrological study because it represents the amount of water potentially available for runoff. Measurement of the amount of water stored in the snowpack and forecasting the rate of melt are thus essential for management of water supply and flood control systems [*Shi and Dozier*, 2000]. Although snow data such as SWE and snow depth are often available in considerable temporal detail from a single point (e.g., the U.S. Snowpack Telemetry (SNOTEL) network [*Serreze et al.*, 1999]), the spatial resolution of snow property data is poor [*Tarboton et al.*, 2000]. Because of complex terrain, these snow attributes exhibit large spatial variability over small distances, so that point measurements such as the SNOTEL network may not adequately represent a basin of interest [*Molotch and Bales*, 2006]. Snow deposition is heterogeneous, with generally greater amounts of snow falling at higher elevations [*Seyfried and Wilcox*, 1995]. Once on the ground, the snow may be redistributed by wind [*Kind*, 1981] or avalanching and sloughing [*Elder et al.*, 1991; *Bloschl et al.*, 1991]. Furthermore, snowpack ablation is also nonuniform because it is controlled by spatially and temporally varying parameters such as temperature, wind, and radiation [*Erickson et al.*, 2005].

[3] Remote sensing instruments on airborne and space platforms are an alternative to ground-based measurements of snow properties. Optical sensors provide important information on snow-covered area in complex terrain, but cannot provide information about snow depth, density, or SWE. The National Weather Service estimates SWE from gamma-ray attenuation in their operational airborne snow survey program (http://www.nohrsc.noaa.gov/snowsurvey/). However, this program can only provide a few observations per year over each of the relatively small flight paths and is not used operationally in complex topography. SWE can also be measured with passive microwave instruments [*Chang et al.*, 1982; *Pulliainen and Hallikainen*, 2001]. While these data provide a valuable estimate of the spatial distribution of SWE on a very coarse grid (25 km) in gentle terrain at high latitudes, they are prone to errors in mountain basins because of changes in grain size and type, forest cover, and other problems that vary over space within a pixel [*Foster et al.*, 2005]. Synthetic aperture radar (SAR) shows promise in measuring snow depth, density, and SWE over large spatial areas but is not currently operational [*Shi and Dozier*, 2000]. Somewhere in between traditional remotely sensed measurements and *in situ* observations, ground based SAR and terrestrial LIDAR can both provide coverage of a local area ($\sim$1 km^2), but are still in the developmental stages, and are relatively expensive [*Luzi et al.*, 2009].

[4] *In situ* measurements of SWE are needed to provide more accurate point measurements, to validate satellite/airborne measurements, and to improve temporal sampling of SWE. Logistical constraints have caused data collection in seasonally snow-covered areas to generally be on a campaign basis with limited instrumentation. Problems of winter access, low air temperatures, and blowing snow cause both equipment malfunctions and problems with consistent and timely maintenance [*Williams et al.*, 1999]. While there are 730 SNOTEL sites spread over 11 western states in the U.S. (including Alaska), and additional snow courses, there are not enough sites to capture all of the spatial variability. Moreover, the footprint of a SNOTEL pillow for measuring SWE at a site is only about 9 m^2 (3 m × 3 m) and does not adequately represent the spatial variation in snow properties near the site [*Molotch and Bales*, 2006]. The two primary factors that must be considered for *in situ* SWE measurements are: 1) the cost of installing and maintaining

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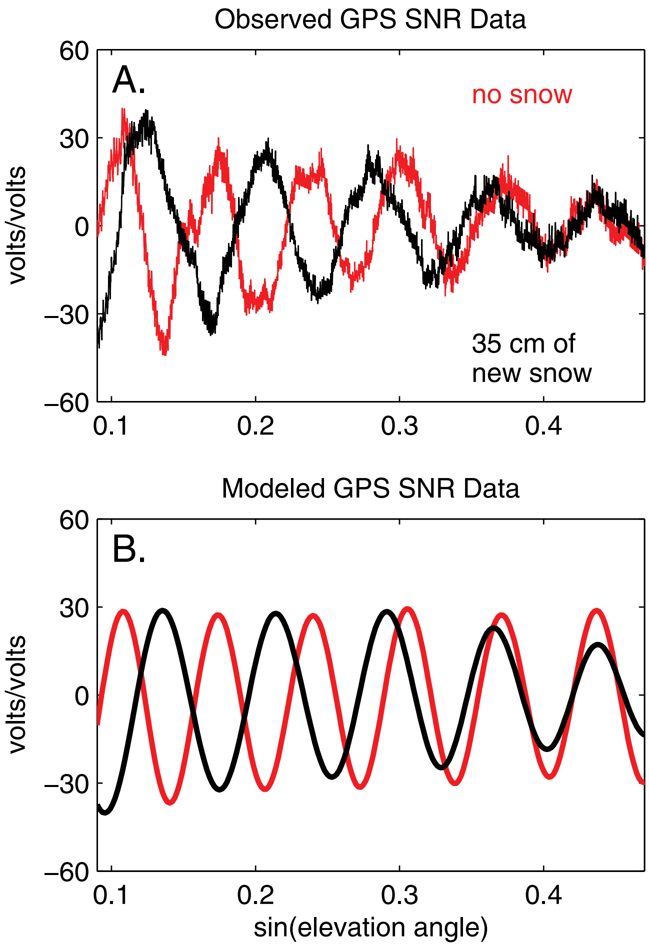

Figure 1. (a) GPS SNR measurements for PRN 7 observed at Marshall GPS site on days 107 (red) and 108 (black) after direct signal component has been removed (see text). Approximately 35 cm of snow had fallen by day 108. (b) Model predictions for GPS multipath from day 107 with no snow on the ground (red), and day 108 after 35 cm of new snow fall had accumulated (black) using an assumed density of 240 kg m^{-3}.

instruments/telemetry systems in difficult/winter environments and 2) the need to measure snow over large areas so that its variability can be properly assessed. The latter is of particular concern as even the most accurate *in situ* snow measurement systems may miss the spatial variability that is common with snow.

[5] In this paper we examine whether GPS receivers might be suitable for measuring snow depth. While we concentrate on snow depth, this is a first step towards measuring SWE using GPS receivers. Given that there are already hundreds of GPS receivers operating in snowy regions of the U.S., it is possible that they could meet the cost requirement for an *in situ* snow network. Most of the GPS antennas operating in snowy regions are several meters above the ground, and thus GPS signals could in principle provide a spatially-integrated measurement over an area of nearly 10,000 m^2 (100 m × 100 m) [*Larson et al.*, 2009]. However, it is not known whether the high-precision GPS systems used by geophysicists and surveyors can be used to infer snow depth.

[6] High-precision GPS systems use antennas that are optimized to track the direct GPS signal; antenna gains for reflected signals – such as those created by snow on the ground – are deliberately made very small. So, while *Jacobson* [2008] recently demonstrated that GPS signal power shows good correlation with snow depth, he did so for a GPS antenna that had been tilted to face the ground. Likewise, airborne GPS bistatic radar systems are flown with antennas facing the ground and are designed to measure reflected signals [*Cline et al.*, 2009]. In order to take advantage of existing GPS systems for an *in situ* snow measurement network, we need to examine the characteristics of GPS signals collected by geodetic-quality GPS receivers, i.e., those installed to measure plate boundary deformation, volcanic inflation, and precipitable water vapor. For these systems, the GPS antennas are always pointed to zenith.

2. GPS Theory

[7] GPS multipath is affected both by the geometry of the reflector with respect to the antenna and the dieletric constant of the reflector. GPS antennas for high-precision applications are designed to suppress multipath, but do not entirely remove it. Multipath from horizontal, planar reflectors – such as the ground – is straightforward to model [*Georgiadou and Kleusberg*, 1988]. The multipath contribution to GPS SNR (signal to noise ratio) data for a horizontal reflector can be represented by $SNR = A \cos(f \sin E + \phi)$, where E is the satellite elevation angle [*Larson et al.*, 2008a, 2008b]. The amplitude A depends on the reflector's dielectric constant and surface roughness, as well as the gain pattern of the antenna. The frequency f will depend on the transmitted GPS frequency (~1.5 and 1.2 GHz), the height of the antenna, the snow density, and on the moisture of the underlying soil. A sample time series of GPS multipathed SNR data is shown in Figure 1a. The red trace was collected with no snow on the ground and ~12 hours before a snowstorm began. Twenty-four hours later, the signal from the same satellite reflects thru ~35 cm of new snow. A clear change in multipath frequency can be seen. We can also see that the amplitude of the SNR data is much smaller at higher elevation angles. This is primarily due to the antenna gain pattern.

[8] The algorithm used to predict GPS SNR for snow is similar to that used for modeling GPS multipath from bare soil [*Zavorotny et al.*, 2009]. It differs only in introducing a uniform planar layer of the snow on the top of soil. Both direct and surface-reflected waves at two opposite circular polarizations are treated as plane waves that sum up coherently at the antenna. The amplitude and the phase of the reflected wave is driven by a polarization-dependent, complex-value reflection coefficient at the upper interface of such a combined medium with a known vertical profile of the dielectric permittivity ε. The reflection coefficient is calculated numerically using an iterative algorithm in which the medium is split into sub-layers with a constant ε. For the soil part, we use a known soil profile model [*Hallikainen et al.*, 1985] that depends on the soil type and moisture. For frozen soil, soil moisture (liquid water) is low, as for very dry soil. For the snow part, we take a constant profile with ε from [*Hallikainen and Winebrenner*, 1992] considering

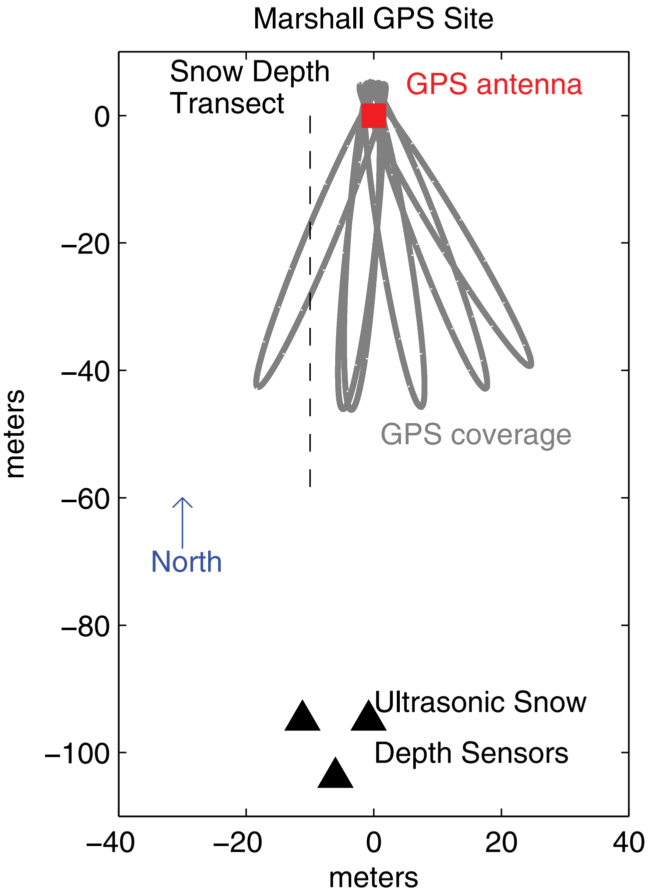

Figure 2. Map view of the Marshall, Colorado site with GPS antenna location (red square), its Fresnel zones at an elevation angle of 5 degrees, and the location of the ultrasonic snow depth sensors (triangles). The location of the measured snow depth transect is also shown (black dashed line).

relatively dry and wet snow layer thicknesses. After calculating the complex amplitude of the reflected wave at each polarization, we multiply it by a corresponding complex antenna gain. The same procedure is applied to the complex amplitude of the direct wave. After that, the modulation pattern of the received power, or the SNR, as a function of the GPS satellite elevation angle is obtained by summing up coherently all the signals coming from the antenna output and taking the absolute value square of the sum.

[9] Model predictions for snow conditions from Figure 1a are shown in Figure 1b. We assumed density of 240 kg m^{-3} for the new snow and a snow temperature of −2°C ($\varepsilon = 1.48 - i2.76 \times 10^{-4}$), after *Jacobson* [2008]. The GPS SNR observations and model predictions for f are in very good agreement: the multipath has a significantly longer period if snow is present as compared with bare soil. Also note that the model amplitudes do not show as pronounced a dependence on elevation angle as the observations. To use model amplitude predictions, further work on antenna gains is required. Only changes in f will be addressed in this study.

3. Measurements

3.1. Site Description

[10] All observations were made at National Center for Atmospheric Research's (NCAR) Marshall Field near Boulder, Colorado (elevation 1728 m). Marshall Field is a winter weather research site that focuses on improving measurements of solid precipitation (snow and icing events). Vegetation at the site is sparse and is classified as short-grass steppe. Instruments include a variety of precipitation gauges, meteorological instruments sufficient for closing the energy balance, and real-time transmission of data. It is also one of ∼1100 sites that make up the Plate Boundary Observatory, a GPS network installed and maintained by UNAVCO under a contract with NSF (http://www.earthscope.org). We used the same GPS receiver/antenna described by *Larson et al.* [2008b] for this study. The antenna is 1.9 m above the ground (Figure S1 of the auxiliary material) and was configured to track the new L2C signal being transmitted on Block IIR-M GPS satellites: PRN 7, 12, 15, 17, 29, and 31.[1] The location of the GPS antenna relative to the snow sensors used in this study is shown in Figure 2. We used only south tracking passes (6 data arcs per day) because buildings obstruct some of the north-tracking passes.

3.2. Field Measurements

[11] Continuous measurements of snow depth were made using three Campbell Scientific SR50 ultrasonic snow depth sensors. These sensors are located above ∼1 m^2 flat platforms ∼100 m south of the GPS station (Figure 2). These platforms are elevated between 8 and 15 cm above the surrounding ground. For the three sensors, we calculated a measurement precision of 0.18, 0.19, and 0.22 cm during periods with no snow on the platform. Hand measurements of snow depth and snow density were made following the protocols of *Williams et al.* [1999].

4. Results

[12] We describe results for two spring 2009 snowstorms for the Marshall, Colorado site (Figure 3). The March 2009 snowstorm began March 26 (day of year 085) at 10:00 UTC and continued for 24 hours with a total of 37 mm of precipitation. Co-located 2-meter wind speed measurements indicate a peak in sustained winds of 12 m/s. At 18:00 UTC on March 27, 2009 we visited the site and confirmed that there was no snow on the antenna. The absence of snow cover on the antenna is likely because of the high winds and sunny conditions, characteristic conditions after winter snow storms in the Front Range of Colorado [*Williams et al.*, 1999]. The temperature was below freezing throughout the day. Snow depth on a 60-meter transect south of the antennas was 30 ± 5 cm (Figure 2 and Table S1).

[13] The second snowstorm began around April 17 (day of year 107) at 00:00 UTC and continued for 48 hours with a total of 105 mm of precipitation. Wind speeds were about 6–10 m/s. Similar to the previous storm, there was no snow on the ground at the start of the storm. Snow fell over much of the 48-hour period on April 17 and 18, although there may have been intermittent rain. We measured the snow transect twice (Table S1). Snow depth was 15 ± 2.4 cm on April 17 and decreased to 8 ± 2.4 cm on April 20. Note that the variability in depth was significantly less for the April

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL039430.

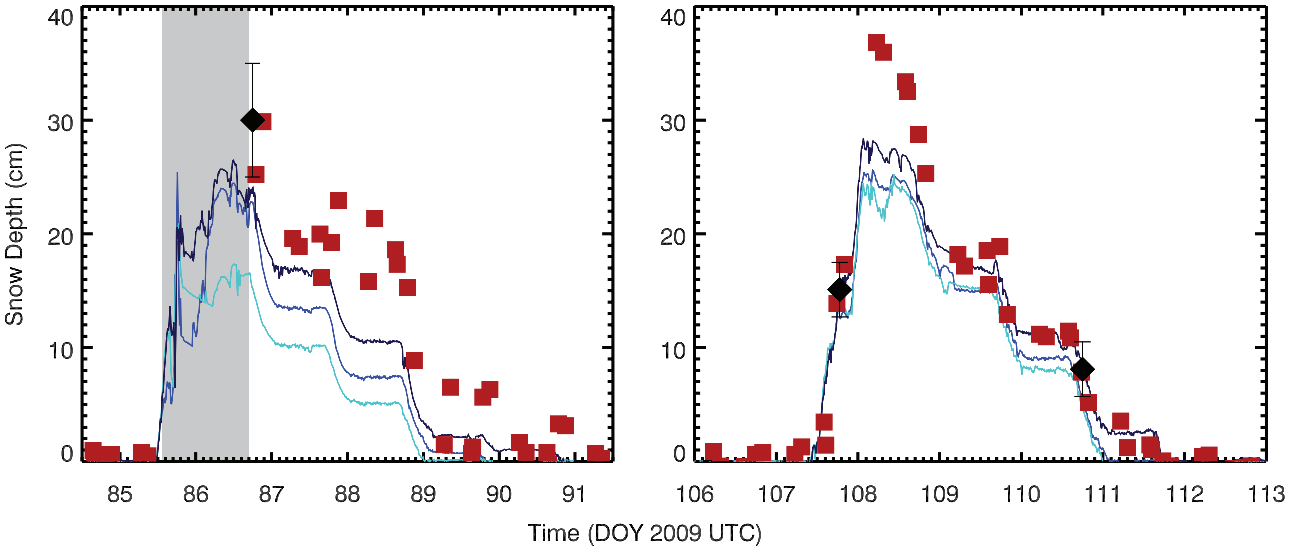

Figure 3. Snow depth derived from GPS (red squares), the three ultrasonic sonic snow depth sensors (blue lines) and field measurements (black diamonds). Bars on field observations are one standard deviation. GPS snow depth estimates during the first storm (doy 85.5–86.5) are not shown (gray region) because the SNR data indicate that snow was on top of the antenna.

storm than was observed in March. On April 17, there was less than 1 cm of snow accumulated on the north side of the antenna, and no snow on the top or south side of the antenna. Snow density measurements were made at the same times as the depth (Table S1).

[14] GPS SNR data are sensitive to but do not directly measure snow depth. Since multipath effects are most pronounced at low elevation angles, only data between 5 and 25 degrees were used in this study. The direct signal component was removed with a 2nd order polynomial. In order to convert changes in GPS multipath data into snow depth: 1) we used a Lomb-Scargle periodogram to estimate the multipath peak frequency *f*; 2) we used the models described in the previous section to match the relationship between *f* and snow depth for various snow densities. For the results shown in Figure 3, we used the model calculations for snow density of 240 kg m^{-3}. We tested lower and higher snow densities (150 and 400 kg m^{-3}) based on our measured values and found that this changed GPS snow depth estimates by 10–12%.

5. Discussion

[15] The GPS multipath measurements agree well temporally with snow depth measured with the ultrasonic sensors (Figure 3). The March ultrasonic data are more variable than the April ultrasonic data, and that is the case with the GPS snow depth estimates as well. The field observations also indicate that the March snow was more variable ($\sigma = 5.0$ cm) than the April snow ($\sigma = 2.4$ cm). The increase of spatial variation in snow depth in the March storm relative to the April storm is consistent with the lower density of the March storm leading to more wind redistribution of snow on the ground. The variation in GPS snow depth during the March storm may thus be due to actual variations in snow depth in different first Fresnel zones. The ultrasonic snow depth sensors are located 50 m south of the GPS first Fresnel zones (Figure 2) and thus may not be measuring the same snow depths. In addition, the ultrasonic sensors are measuring snow accumulated on a platform that is raised 8–15 cm above the surrounding ground surface. This may lead to a low bias in the ultrasonic depth measurements during periods of blowing snow.

[16] Accuracy of the GPS snow depth estimates is limited by our models for snow and the assumptions made therein. For example, our model assumes a planar layer of snow when we know that snow layers are not planar. Also, we currently use all data between 5 and 25 degrees elevation angle to estimate *f*; this may not be optimal for snow sensing. At higher elevation angles, the first Fresnel zones become smaller (and closer to the antenna) [*Larson et al.*, 2008b]. This means that data 5 meters from the antenna have greater weight than data 25 meters from the antenna. In the future, we plan to compare different retrieval algorithms, including variations in model predictions and elevation angle cutoffs. We also used the average measured snow density value whereas we know the snow was drier in March and became wetter during the April storm.

[17] For this first assessment of GPS as a snow sensor, we used only multipath frequency and did not attempt to estimate snow density. The model predictions we discussed in the previous section indicate that amplitude and ϕ can be used in conjunction with *f* to determine both snow depth and snow density, and thus SWE. In order to use the amplitude data for GPS signal power data, we first need to better characterize the antenna+radome gain pattern and temperature effects. This study was limited to measurement of snow properties by GPS during transient snow events. How effective GPS will be at measuring snow properties with a continuous seasonal snowpack composed of multiple layers with varying densities and grain sizes and types is unknown and warrants further investigation.

[18] As a final caveat, using GPS as a snow depth sensor is more challenging when snow or ice accumulates on top of the antenna. We can determine the presence of ice/snow on top of the antenna by evaluating the direct GPS signal

power (rather than the multipathed signal). We have used this formulation to exclude some snow depth estimates during the March storm. It is not at all clear that we can simultaneously model snow on top of the antenna and on the ground. In special situations, such as when the antenna is completely buried by snow, it may still be possible to estimate snow depth. Many of the Earthscope GPS sites in Alaska show these drastic effects (J. Freymueller, personal communication, 2008).

6. Conclusions

[19] GPS data collected with a geodetic receiver operating to measure plate boundary deformation show excellent agreement with traditional snow sensors and field observations. Unlike most GPS reflection experiments [*Jacobson*, 2008; *Cline et al.*, 2009], this study used an antenna designed to suppress reflections and was pointed towards zenith. This opens up the possibility that GPS networks operated by international geophysical and geodetic agencies could be used for cryosphere studies. Currently GPS geodesists only consider snow effects when they cause large systematic variations in position [*Jaldehag et al.*, 1996]. This study suggests that some GPS sites could be used to augment existing snow sensor networks such as SNOTEL.

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