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Monitoring snow depth by GNSS reflectometry in built-up areas: A case study for Wettzell, Germany

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Abstract*—Snow storage dynamics is essential to predict floods, to quantify water resources for human use and irrigation, and to assess the risk of avalanches. Recently, Global Navigation Satellite System (GNSS) ground stations have been successfully used to continuously estimate snow depth at an intermediate scale of about 1.000 m^2 around the stations. In this study, GNSS signal-to-noise ratio (SNR) data at the station Wettzell, Germany, are used to estimate snow depth variations from 2012 to 2015. The station Wettzell is located in a built-up area. The most challenging task at this site is to separate the GNSS reflections from the ground and from surrounding buildings. We modified the interference approach previously used for snow depth estimation by using the phase of the multipath interference pattern instead of their frequency. Additionally, we complemented the analysis by including satellites transmitting the L2P signal into the processing. We studied the performance of the L1 signal. The derived GNSS snow depth ranges between 3 cm and 25 cm and corresponds well to in-situ observations by an ultra-sonic sensor, with a correlation of 0.8 for daily time series. The residuals of GNSS snow depths compared to the ultra-sonic sensor reveal a RMSE of 4.3 cm for the L2 and 5.9 cm for the L1 signal with a small bias of 1 cm. The results show that the existing data of the global GNSS tracking network promises to provide valuable complementary snow depth observations to the existing sensors at several hundred sites worldwide, including urban areas.

***Index Terms*— Global Navigation Satellite System (GNSS), reflectometry, remote sensing, snow depth**

I. INTRODUCTION

ONE-sixth of the world population depends on the freshwater stored in snow packs [1]. Snow melt water released from the mountain reservoirs provide water for drinking and irrigation, especially in the dry summer periods. The quantification of mountain water resources is essential for human use [2]. Snow storage gives also relevant information on flood prediction. During intense solar radiation and strong rain events the qualitative and temporary meltwater predictions are highly in demand by decision makers in the field of hydropower generation and flood prevention [3]. Additionally, the assessment of avalanche risk is strongly dependent on information on snow pack properties like density, wetness and depth [4].

Snow storage is difficult to quantify because it is highly variable in space and in time. Snow pack observations from in-situ measurements are restricted to a small number of sites, they often are invasive, or rely on empirical calibration functions that are hardly transferable to other locations [5]. Manual ground based measurements like stake observations are carried out infrequently and lack high temporal resolution [6]. Automatic ground based measurements, e.g., ultra-sonic or gamma radiation sensors provide information on temporal dynamics of accumulation and ablation. However, with their small sampling area of 1-2 m they miss spatial variations and are very sensitive to wind-induced snowdrift. Large scale snow products derived from remote sensing

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satellites provide snow cover rather than snow depth [7]. The direct measurement of snow storage, i.e., snow-water equivalent, can be achieved by few in-situ devices only, such as lysimeters or snow pillows.

Estimates of snow depth at intermediate scale of about 1.000 m^2 were successfully obtained from measurements with GNSS ground based receivers, which were set up for geodynamic applications [8]. The authors demonstrated that these geodetic GNSS instruments, which are optimized to track the direct signals from the satellites, could successfully also be used to measure the reflected signals. These reflected signals contain information on water content [9] and snow depth. The snow depth retrieval algorithm is based on the analysis of the interference pattern in the power of the GNSS signal. The interference occurs as result of the simultaneous reception of the direct signal from the moving GNSS satellite and the signal reflected by the ground surface. This interference pattern depends on the height difference between the GNSS antenna and the reflection point, which in the case of snow depth varies over time [10].

Snow depth time series of multiple years were presented for several GNSS stations of the EarthScope Plate Boundary Observatory (PBO) in the Rocky Mountains [11]. A comparison of snow depth observations from nearly 100 GNSS stations of the PBO network with model estimates from the Snow Data Assimilation System (SNODAS) shows for 80% of the sites an agreement of better than 15 cm root mean square error [12]. Nievinski and Larson [11, 13] developed a forward and inverse model for the estimation of snow depth from GNSS signals. Jacobson [14, 15] proposed a method to derive snow water equivalent combining snow depth and snow density. In these studies, both, snow depth and density, were estimated from reflected GNSS observations by applying a nonlinear least square fitting technique. However, in contrast to our approach, the setup of [14, 15] was based on a GNSS antenna that was rotated towards the reflecting surface. From GNSS based snow depth and modeled snow density, snow water equivalent was estimated with an accuracy of 3.5 cm for 18 PBO sites in western U.S. [16, 17].

Koch et al. [18] used measurements of low-cost GNSS receivers (Fastrax IT430) to derive snow liquid water content. The authors installed three GNSS antennas, one above the snow surface mounted on a 4 m high pillar and two buried beneath the snowpack. The method is based on the attenuation of the GNSS signals in the snow, which is influenced by the snow wetness. Applying a semi-empirical model of electromagnetic wave transmission through snow, the authors showed that the signal to noise ratio (SNR) from the GNSS signal could give valuable information on the dynamics of the snow liquid water content. Additionally, to the above mentioned snow depth estimation based on SNR data, the snow depth can also be derived by using the dual-frequency and triple-frequency phase combination methods [19, 20]. The snow depths estimated from geodetic receivers using those methods are accurate to about 10 cm [19].

In contrast to previous studies, where the GNSS stations were situated on bare soil or grassland, we assess the accuracy of GNSS-based snow depth measurements in built-up areas with several constructions in the proximity of the station. Many GNSS stations of national GNSS networks are installed in urban areas with buildings in their direct environment, e.g., around 300 stations in Germany (SAPOS) [21], around 500 stations in France (RGP) [22] and around 2,000 stations in the United Sates (CORS) [23]. Additionally, we extended our analysis to additional GNSS frequencies. Previous studies focused on snow depth estimation from the new civilian L2C signal, which has a higher signal power, compared the L2P signal [24]. In 2009, there were only 7 satellites (PRN 5, 7, 12, 15, 17, 29, 31 from GPS block IIRM) transmitting the L2C signal and 24 satellites transmitting L2P. With the installation of block IIF, 10 additional L2C transmitters were sent into the orbit until today (PRN 1, 3, 6, 8, 9, 24, 25, 26, 27, 30). In urban environments, buildings restrict the reception of reflected signals from the ground to very few satellites. The inclusion of the L2P satellites in the analysis could increase the number of available satellite tracks for the snow depth estimation, especially for historical data. We also analysed the L1 signal because L1 single frequency receivers are less expensive than dual frequency receivers. The question is how accurate snow depth can be derived from these L1 receivers. We validate the snow depth estimates derived from L1, L2P and L2C SNR data with in-situ measurements by an ultra-sonic sensor. Furthermore, we investigate whether historical GNSS observations with a 30 s sampling rate, which extend for several stations back into the early 1990s, could provide a valuable data source for long-term snow depth estimation.

II. SITE AND DATA DESCRIPTION

The study site is situated in the low mountain range of the Bavarian Forest, Germany, at 49.144°N, 12.879°E with an elevation of 610 m (NN). The period with snow cover is relatively short and snow depth rarely exceeds 30 cm. Winter temperatures usually vary around the freezing point. Thus, the snow is rather wet and melts quickly. The GNSS station Wettzell (WTZR) is part of the global tracking network of the International GNSS Service (IGS). It is also part of the geodetic fundamental station Wettzell. We have chosen this GNSS station for our case study because independent snow depth measurements taken with an ultra-sonic sensor are available for validation next to the GNSS antenna at a distance of about 130 m.

The common observation period of GNSS and the ultra-sonic sensor is from January 2012 to April 2015. This provides the possibility to validate GNSS derived snow depth for four winter seasons. The GNSS antenna is installed on the roof of a 7.8 m high building (Figure 1). The environment of the station is slightly undulating; terrain elevation varies by about 20 m in a radius of 100 m around the antenna. The surroundings of antenna are inhomogeneous, consisting of grassland, sealed surfaces and built-up areas, typical for an extensive geodetic observatory with different instruments such as telescopes, platforms, and operation facilities spread out over the site. In the surroundings of the GNSS station, several buildings and trees restrict the observation of GNSS reflections (Figure 1).

A. *GNSS data*

The power of the GNSS signal is a standard observable besides the widely used phase and code observations. The SNR is the ratio of the GNSS signal power to the measurement noise. It is given in a logarithmic decibel (dB) or decibel-Hertz (dB-Hz) scale and recorded as signal-to-noise ratio (SNR) in standard Receiver Independent Exchange Format (RINEX) observation files [25]. The SNR is used in operational applications to check the signal quality and characteristics of electromagnetic noise in the close environment of the GNSS station. The SNR depends mainly on the antenna gain pattern, the tracking algorithm in the receiver, the power of the signal transmitted by the GNSS satellite and, for low elevation angles, also on the power of the reflected signal [9].

The GNSS station Wettzell was installed in February 1995 and SNR data are stored in the data files since January 2006. The GNSS data were archived with a 30 s sampling rate. Since January 2012, data have been stored with a 1 s sampling rate. From January 2009 onward, the site is equipped with a geodetic Leica antenna of the type LEIAR25.R3 and a radome LEIT (Leica External GPS L1/L2/L5 chokering antenna) and a receiver of the type LEICA GRX1200GGPRO (Leica triple frequency GPS L1/L2/L2C/L5), which was replaced by a Leica GR25 in Feb 13 2014. The SNR is recorded with a precision of 0.05 dB.

On a flat and horizontal ground, the GNSS signals are reflected from an elliptic area, which can be described by the elliptically shaped first Fresnel zone

$$a = \frac{b}{sinE}; b = \sqrt{\frac{\lambda h}{sinE} + \left(\frac{\lambda}{2sinE}\right)^2} \quad (1),$$

where a represents the semi-major axis and b the semi-minor axis, λ the GNSS wavelength, h the height of the antenna phase center above the reflecting surface and e the satellite elevation angle [11]. For the GNSS station Wettzell with its antenna installed on the roof of an 7.8 m high building, the first Fresnel zone has the dimension of a=60 m and b=5 m for a GNSS satellite at an elevation angle of 5°. The major axis of the ellipse is aligned in the direction of the satellite-antenna vector. When the satellite is approaching the zenith on an ascending orbit, the ellipse becomes smaller and moves towards the antenna (Figure 2). The reflections start at a distance of ~200 m from the GNSS antenna and approach until 15 m for a satellite pass from 5° to 30° elevation. For this passage the satellite needs about one hour. Due to the buildings and trees surrounding the GNSS station, strong ground reflections could only observed for four satellite tracks in the southwest (PRN 2, 14, 17 and 25).

B. *Ultra-sonic snow height sensor*

Continuous measurements of snow height at the study site are carried out at a distance of ~130 m to the west of the GNSS station. Two ultra-sonic sensors (type Sommer USH-8) were placed at 2 m height above the soil surface. The diameter of the sensed area on the ground is about 0.4 m. The distance between the two sensors is about 45 m. While the first sensor measures snow depth over a planar plastic surface of a snow pillow, the second sensor is installed over grassland. The sensors are equipped with an internal temperature compensation to account for changing sound velocities as a function of air temperature. Possible disturbance of the ultra-sonic measurements by high wind speed were not accounted for. However, as the wind speed at the site usually was below 2 m/s, we consider this effect to be small. The measurement accuracy of an ultra-sonic device within its footprint is better than 3 cm [26]. The comparison of the daily time series of the two sensors shows a RMS difference of 2.6 cm (Figure 3).

III. DATA ANALYSIS

We analyzed data of the GNSS station for the period January 1, 2012 to April 30, 2015. We partitioned the SNR data in tracks per satellite number, azimuth quadrant and rising and setting satellites. In a first processing step we applied the interference pattern approach proposed by [11]. We fit a second order polynomial to the SNR. By subtracting this polynomial from the SNR data we isolate the interference pattern. We analyze the SNR interference pattern for satellites with elevation angles ranging between 5° and 30°. For the reason of linearity we convert the amplitude of the SNR, which is given in logarithmic dB-Hz units, into volts. The SNR interference pattern shows a periodic signature, which is a function of the satellite elevation angle e (Figure 4). When $\sin(e)$ is used as independent variable the frequency f of the multipath pattern is constant assuming a locally planar and horizontal surface [27]. The frequency $f = \frac{4\pi h}{\lambda}$ of the interference pattern depends on the wavelength λ of the GNSS carrier and the height h of the GNSS antenna above a reflecting planar surface. Snow depth is calculated as the difference between the GNSS reflector height above the soil and the snow surface. The assumption that the GNSS signal is reflected from the snow-air interface holds very well, as the snow in Wettzell is mostly wet. The frequency of the interference pattern was calculated using the Lomb-Scargle periodogram method [28], an algorithm to calculate the spectral power for irregularly spaced time series. Satellite tracks which contain less than 2000 data points (equal to roughly 30 minutes of observation) or with a weak coherent reflection component (the dominant frequency does not exceed two times the background noise) were discarded. The inhomogeneous environment prevents the reception of reflection from the ground for most of the satellites transmitting the L2C signal. Hence, in contrast to Larson and Nievinski [11], we do not restrict our analysis to L2C satellites but include all satellites into the analysis.

For the station Wettzell the Lomb-Scargle periodogram with the frequency converted into reflector height often shows two significant peaks (Figure 4 bottom panel). The larger peak at 7.8 m corresponds to the reflections from the ground and the smaller peak at 0.8 m is related to reflections from the metal roof of the building. The dominant frequency not always corresponds to the reflections from the ground. Especially on days with snow cover (doy 25 to 50 in 2013) the reflections from the roof show larger amplitudes than the reflections from the ground (Figure 5). For more than 20% of the analysed tracks the strongest reflections come from the roof and not from the ground. The reflections from the roof cause outliers in the snow depth estimates. We therefore modified the algorithm proposed by Larson and Nievinski [11] for rural areas. In order to avoid reflections from the roof we restricted the range for picking the largest amplitude. The range was derived by the median of the reflector height plus minus 2 m.

In contrast to previous studies on snow depth estimation with GNSS reflectometry, we extended the analysis by a second processing step. This step is based on the adjustment of a sinusoidal to the interference pattern, which was proposed by Larson et al. [9] for soil moisture estimation. We fixed the reflector height to the value estimated for snow free soil. As a reference height for the snow free surface we estimated specifically for each satellite track the median reflector height within the month of November. For Wettzell the month of November best fulfils the assumption that the reflections are from the soil surface. This month shows only little vegetation, high soil moisture (34 - 37 Vol%, based on in-situ measurements of 31 soil moisture probes at a depth of 0-35 cm in 2013, not shown here) and there is no snow. The reference reflector height represents an average height over the area of the Fresnel zone for the whole satellite pass between 5° and 30°. We adjusted the sinusoidal (Equation 2) to the interference pattern and estimated amplitude A and phase offset Φ.

$$SNR = A cos\left(\frac{4\pi h}{\lambda}\sin(e) + \phi\right) \quad (2)$$

In the next step the phase was reduced by a constant offset, so that the phase values for the snow free periods corresponds to reflections from the upper surface of the soil. This constant offset was calculated as average phase $\overline{\Phi_N}$, for the month of November. The reduced phase variations $\phi - \overline{\Phi_N}$ were converted from degree into radiant and into the unit of length accordingly to equation (3). The resulting variations in reflector height correspond to the snow depth SD_{GNSS}.

$$\mathrm{SD_{GNSS}} = (\phi - \overline{\Phi_N})\,\lambda\frac{\pi}{360°} \quad (3)$$

Equation 3 yields the conversion factors of the phase estimates (in degree) into snow depth (in centimetre) of 0.166 (1/6) for the L1 and 0.213 (1/5) for the L2 signal. The proposed second analysis step works for snow depths smaller than one wavelength of the interference pattern. For higher snow depths a phase unwrapping is necessary or the snow depths could be directly derived from the Lomb Scargle periodogramm as proposed by Larson and Nievinski [11]. Finally, we calculated a common daily mean for all satellite tracks that pass at different times during the day.

IV. RESULTS

SNOW DEPTHS FROM REFLECTOMETRY

The results are based on data with a 1 s sampling rate. The resolution of the dominant frequency and the estimation of the phase variation from the SNR interference pattern are less precise for 30 s data than for 1 s data (Figure 4) (Vey et al. 2015). The 1 s data are available since January 1, 2012 until April 30, 2015. The results are based on data from L1, L2P and L2C. Due to the constructions in the station environment we received dominant ground reflections only from the satellites PRN 12, 14, 17, 25. While the satellites PRN 12, 17 and 25 transmit the modernized L2C signal, the satellite PRN 14 transmits the less precise L2P signal only. The accuracy of the phase estimates from the least square adjustment of the sinusoidal to the interference pattern depends on the used signal. The phase accuracy is 4.5°, 3.9° and 2.2° for the L1, L2P and L2C signal. This corresponds to an accuracy of the snow depth of 0.8 cm, 0.7 cm and 0.4 cm, respectively.

The snow depth for the GNSS station WTZR was calculated as mean over the above selected satellite tracks. The standard deviation of the snow depth from a single satellite track compared to the common mean is typically 8 cm. The final snow depth estimate represents a spatial and temporal average of all observations analyzed during one day (Figure 6). The footprint of the spatial average from all satellite tracks used covers about 5,000 m^2. The derived snow depths show small values with a maximum of 25 cm in the years 2012, 2013 and 2015. The year 2014 had nearly no snow with a maximum snow depth of only 7 cm. In general, the period with snow cover extends from December to February. Largest snow depths are typically recorded for February.

COMPARISON WITH INDEPENDENT SNOW MEASUREMENTS

An average snow depth derived from the observations of the two ultra sonic sensors over the period from January 2012 until April 2015 was used for validation. The GNSS derived snow depth dynamics are able to reproduce the snow accumulation and thawing events for all four winter seasons (Figure 6). Even small events of only 3 cm snow accumulation (e.g., DOY 18 in both 2013 and 2014) are well observed by the GNSS measurements. However, in some cases differences of up to 10 cm can occur between GNSS and ultra-sonic measurements. One reason for these large residuals can be the different location and footprint of the two methods. The ground surface is very inhomogeneous, consisting of grassland, pavement, concrete or gravel (Figure 1). The different surfaces have different thermal properties, which may affect snow accumulation and melt and, thus, snow depth. This strong spatial heterogeneity is also reflected in the deviations of 8 cm along the single satellite tracks compared to the average of all tracks.

The snow depths, derived from GNSS (L2C and L2P) and the ultra sonic sensor, are highly correlated with a correlation coefficient of $r^2=0.78 \pm 0.06$ (Table 1). The regression analysis shows a good agreement between both data sets with a regression slope of 1.23 ± 0.01 and intercept of -1.5 ± 0.05 (Figure 7, top panel). On average the GNSS snow depth is slightly smaller as from the ultra sonic sensor. This could be related to the uncertainties in the assumption made for the calibration of the phase to the snow free level. We assumed that the effect of vegetation could be neglected for the month of November used as reference. However, even in November there is some sparse and short vegetation on the grassland area. Thus, the GNSS signal might not only be reflected on the soil surface but also to some extent on the vegetation [30]. An effective vegetation height of 1 cm for grassland would translate into a snow-free reference height that is 1 cm to high, resulting in an underestimation of snow depth by 1 cm. Another error could be caused by the penetration of the GNSS signal into the soil in the snow-free reference period of November. However, with soil moisture above 34 Vol % we assume this effect to be only in the order of a few millimeters [9]. Additionally, any penetration of the GNSS signal into the soil would cause too large instead of too small snow depth estimates. The influence of the snow density of the snow pack on the reflection of the GNSS signals is much smaller than the air-snow interface [24]. For Wettzell the penetration effect of the GNSS signals into to snow is supposed to be rather small as the snow is very wet most of the time. Bias in the topography due to undulations in the surface remains stable, as the ground tracks of the GPS satellites used do not change over time. Overall, we found a very good agreement between the GNSS derived snow depth and the ultra-sonic observations showing a RMSE difference of 4.3 cm.

The results presented above are based on the SNR of the L2 signal (average of estimates from L2C and L2P). As a first approach for the accuracy of snow depth estimates from single frequency receivers we validated the snow depth from the L1 signal of the dual frequency receiver at Wettzell. The comparison of the $GNSS_{L1}$ derived snow depth with the snow depth from the ultra sonic sensor shows a correlation of $r^2=0.70 \pm 0.09$ (Table 1). The accuracy of the $GNSS_{L1}$ snow depth estimates from this comparison is 5.9 cm. The regression analysis reveals a slope of 1.31 ± 0.01 and a regression intercept of 0.9 ± 0.07 (Figure 7, bottom panel). The small positive bias of the $GNSS_{L1}$ snow depth estimates might result from the higher scatter of the phase in the snow free period, which translates into a larger uncertainty in the estimation of the reference phase. The snow depth estimated from SNR of the L1 signal is with an accuracy of 6 cm less precise than snow depth from the L2 signal. However, an average snow depth over an area of several 100 m^2 with an accuracy of 6 cm is still good for many hydrological applications.

V. CONCLUSIONS

This case study for the IGS station Wettzell (WTZR) shows that even in an unfavourable built-up environment daily snow depth estimates from GNSS data capture the accumulation and ablation due to precipitation and melting very well. The GNSS derived snow depth estimates from four winter seasons are highly correlated with the snow depth observations from ultra-sonic sensor. Small deviations of at most 10 cm between the GNSS and ultrasonic snow depths are primarily related to the spatial heterogeneity in snow depth and the different footprints and locations of both observing techniques. GNSS operates at intermediate scale and the snow depth is an average over several 100 m^2. Thus, GNSS is less sensitive to small scale snow redistribution due to wind drift in contrast to ultra sonic sensor measurements which are point measurements representative for less than 1 m^2. Snow redistribution due to wind drift at Wettzell is rather small because of low wind speed and mainly wet and heavy snow. The very good agreement of the snow depth measurements from the two different ultra sonic sensors at different locations confirms that there is a rather small spatial variability of snow depths. Effects of man-made redistribution of snow by clearing the walkways at the Wettzell station terrain are expected to be negligible as the walkways cover only a small area of the footprint and the maximum snow depth is 25 cm.

The good agreement between GNSS and ultrasonic snow depths (RMSE of 4.3 cm) implies that even GNSS stations within urban structure can serve as accurate snow sensors. Thus, additionally to the global GNSS networks installed for plate boundary observations with stations mainly in rural environments, thousands of stations of the national GNSS networks operated for surveying tasks could provide valuable information on snow depth. In Germany alone, the national GNSS reference network SAPOS consists of around 300 stations (SAPOS) [21]. Most of these stations are installed in urban environments. The SNR of the L1 and L2P signals from geodetic antennas can provide reliable snow depth estimates, but less accurate than those based on the L2C signals. However, only few ground reflections from L2C are available for urban environments and historical data. The L2P reflection can improve the spatial coverage with only slightly decreased accuracy compared to the results from L2C signal. Another advantage of the L2P signals is that it broadens the applicability of the snow depth estimation to historical GNSS observations when no L2C signal was available.

Snow depths derived from the L1 reflections are accurate to 6 cm. This is still very good for many hydrological applications. Extending the snow depth estimation to the L1 signals extends the application to single frequency L1-only GNSS receivers, which are much cheaper than geodetic dual frequency receivers. Those receivers could be used to increase the station density in networks in remote areas. In future, snow depth estimates based on GNSS signals could be obtained in near real time and assimilated into hydrological models as one of the descriptors of water storage.

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Table 1: Comparison of the snow depth estimates from GNSS and the ultra sonic sensor. The statistics refer to the scatter plot in Figure 6. The confidence interval is based on a 95% level of significance.

	Correlation r^2	Regression slope	Regression intercept (cm)	RMSE (US-GNSS) (cm)
L2P & L2C, 1sec	0.78 ± 0.06	1.23 ± 0.01	-1.5 ± 0.05	4.3
L1, 1sec	0.70 ± 0.09	1.31 ± 0.01	0.9 ± 0.07	5.9

Fig. 1: Antenna of the GNSS station WTZR (Wettzell, Germany). The photo was provided by Uwe Hessels from the Federal Agency for Cartography and Geodesy.

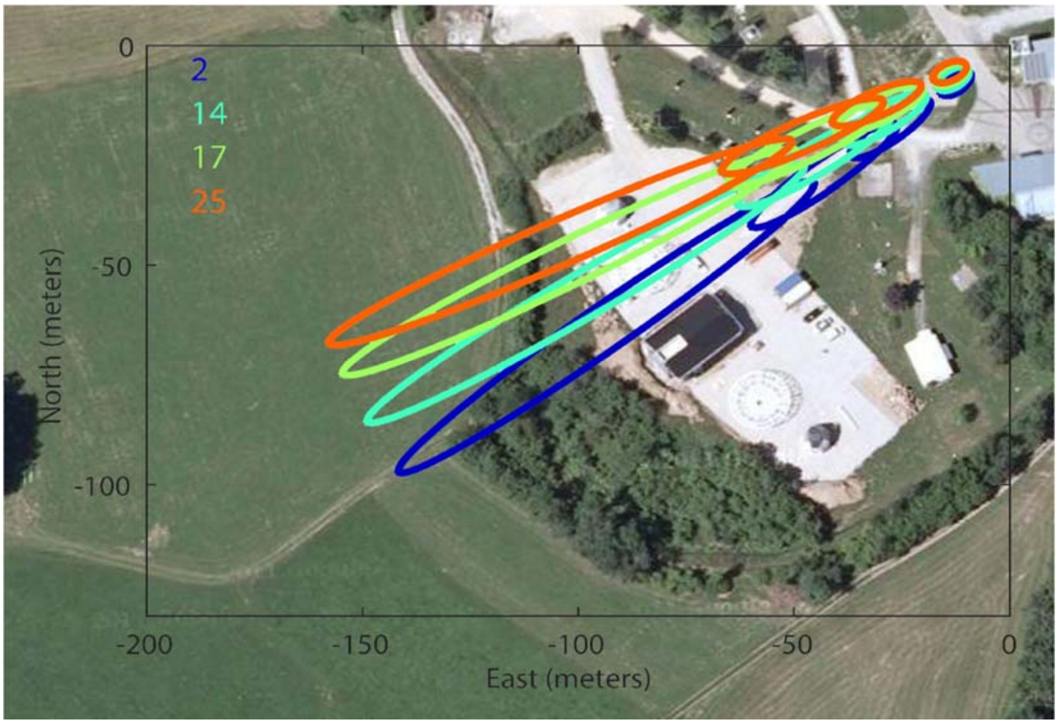


Fig. 2: Areas indicating the coverage of ground tracks of the reflected signals. The North/East distances are related to the antenna position (top right). The Fresnel zones are shown for satellite elevation angles of 5°, 10°, 15° and 30°. The higher the satellite rises, the smaller is the ellipsis and the closer it moves towards the antenna. The numbers at the top left are the PRN numbers of the GPS satellites used in this analysis.

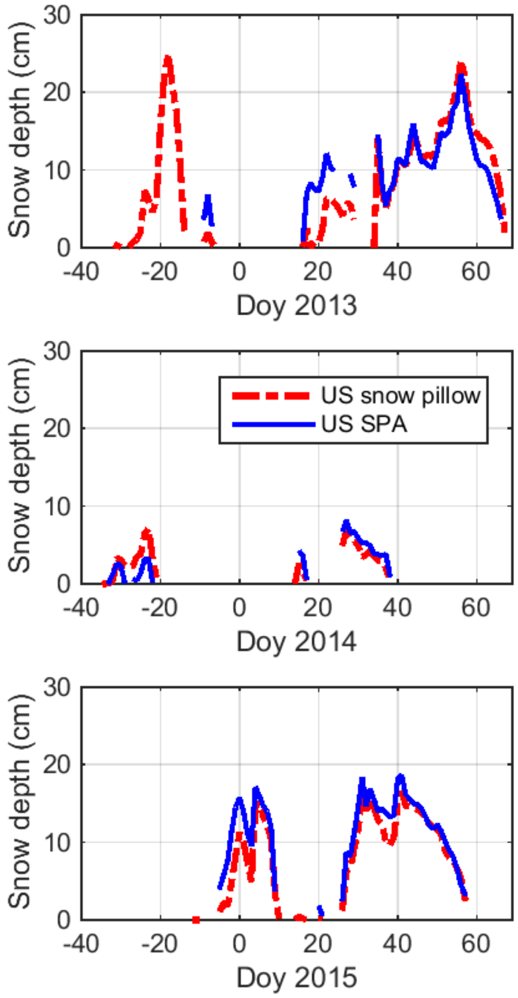


Fig. 3: Snow depth recorded by the two ultrasonic sensors (US) at Wettzell at sites ‘snow pillow’ and ‘SPA’.

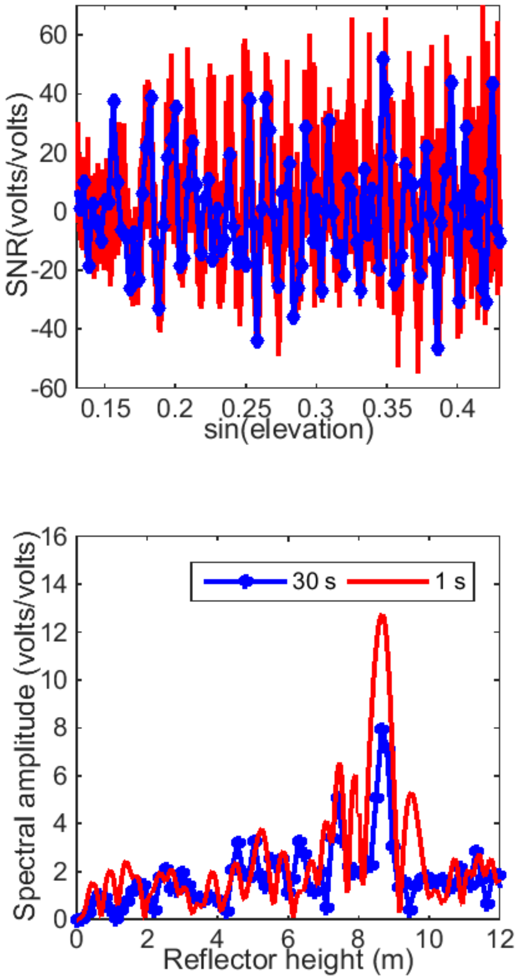


Fig. 4: Signal to noise ratio (SNR) for the GPS satellite PRN 17 on January 1, 2013. The top panel shows the SNR of the reflected L2C signal. The bottom panel shows the Lomb-Scargle periodogram of the SNR. The two peaks at 7.8 m and 0.8 m for the 1 s data represent the reflections from the ground and from the roof, respectively. For the 30 s data no dominant peaks could be estimated.

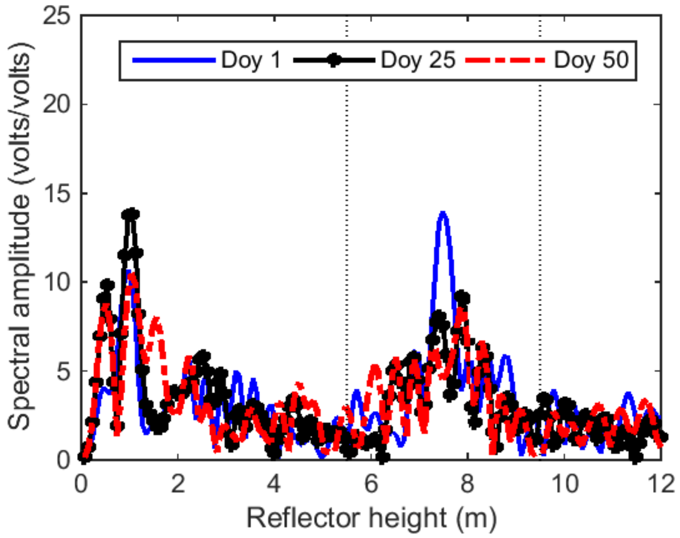


Fig. 5: Lomb-Scargle periodogram of the SNR for GPS satellite PRN 17 at days with snow (doy 25 and 50) and without snow (doy 1). On doy 25 and 50 the reflections from the roof of the building have a larger amplitude than the reflections from the ground. Dotted lines mark the range that was defined for the search of the maximum in the amplitude.

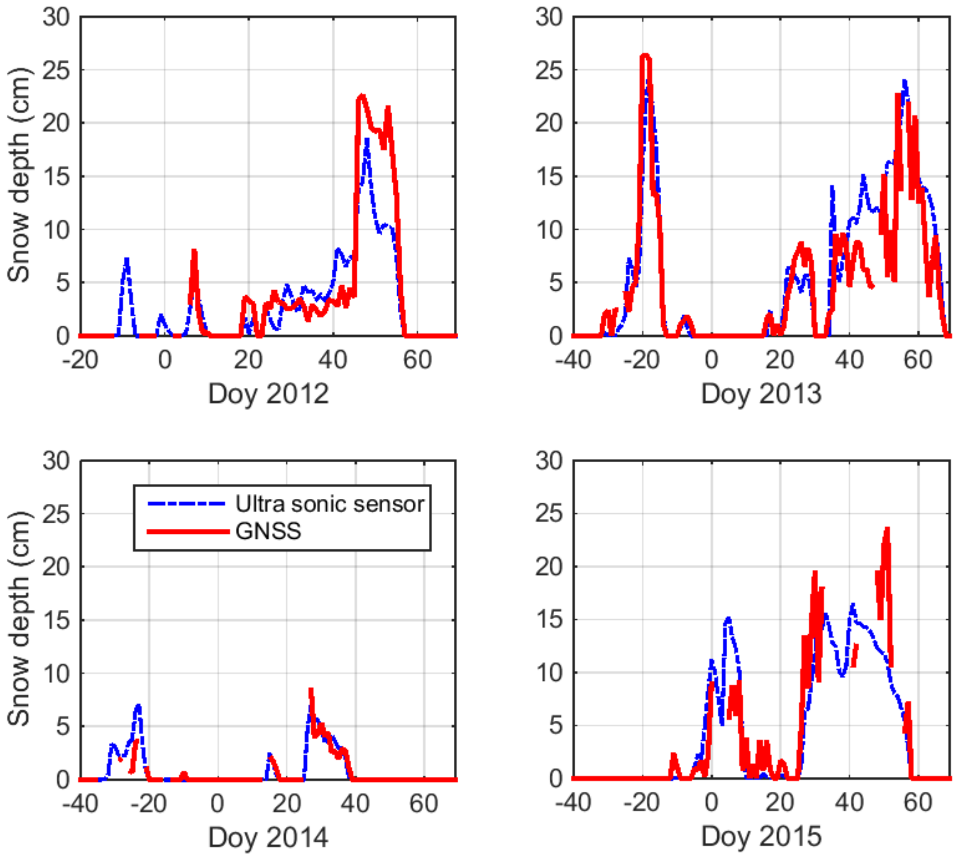
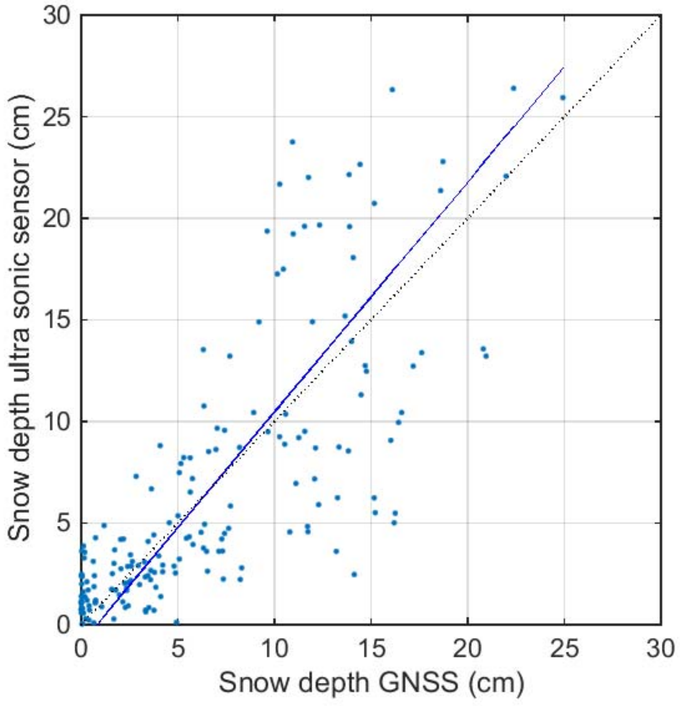


Fig. 6: Comparison of the snow depth from GNSS data (average of estimates from L2C and L2P signals, solid red) and the ultra sonic sensor (dashed blue).



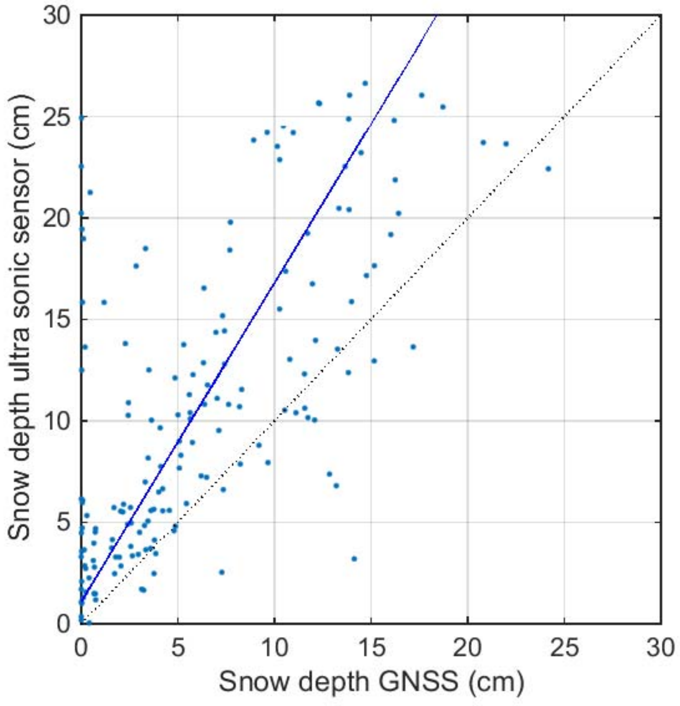


Fig. 7: Scatter plot of the snow depth from GNSS data and the ultra sonic sensor for the period from January 1, 2012 to April 30, 2015. Top panel shows the comparison for snow depth derived from the L2 signal (average of estimates from L2C and L2P) and bottom panel from the L1 signal. The blue line represents the regression line and the black dotted line the ideal 1:1 line. Statistics on the comparison are given in Table 1.

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